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Design and Development of EPICS Based RF Conditioning System for the High Power RF Components of Charged Particle Accelerators

S.M. Shajedul Hasan
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To the Graduate Council:

I am submitting herewith a thesis written by S.M. Shajedul Hasan entitled "Design and Development of EPICS Based RF Conditioning System for the High Power RF Components of Charged Particle Accelerators." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Mostofa K. Howlader, Major Professor

We have read this thesis and recommend its acceptance:

Yoon W. Kang, Michael J. Roberts, Paul B. Crilly

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew
Vice Chancellor and
Dean of Graduate Studies

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Design and Development of EPICS based RF Conditioning System for the High Power RF Components of Charged Particle Accelerators

A Thesis
Presented for the
Master of Science
Degree

The University of Tennessee, Knoxville

S.M. Shajedul Hasan

August 2005

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Dedication

This thesis is dedicated to my parents.

Acknowledgements

I would like to thank my supervisor Dr. Mostofa K. Howlader for his continuous guidance throughout my academic life in the University of Tennessee. I also would like to thank Dr. Yoon W. Kang, my supervisor in the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) for giving me the opportunity to work there. This thesis would not be accomplished without his guidance, encouragement, and his constructive comments. I also would like to give my thanks to my committee members, Dr. Paul B. Crilly and Dr. Michael J. Roberts.

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Finally, my thanks go to my wife, Rimi Ferdous, for her continuous support and her encouragement in my work.

Abstract

Charged particle accelerators use various vacuum windows on their accelerating RF cavities to pass very high RF power through for the acceleration of particles. The accelerating cavities and the windows should be cleaned, baked and fully RF conditioned to eliminate poor vacuum caused by outgassing and other contamination. The linear accelerator (Linac) in the Spallation Neutron Source (SNS) contains various accelerating cavity structures and RF conditioning of their high power vacuum windows is necessary for present work as well as future upgrade and development. An example is the coaxial fundamental power coupler (FPC) with an annular alumina ceramic window for each of the 81 superconducting RF cavities in the SNS Linac. The FPC's need to be tested up to 650 kW peak in traveling wave and 2.6 MW in standing wave in 1.3 microsecond 60 pulses per second RF. 805 MHz, 550-kW klystrons (700 kW maximum) are the main power source of the superconducting Linac and the conditioning power source of the FPC's. The conditioning process has to be controlled very carefully not to damage the window; with the high power RF the initial vacuum is unpredictable and any unsafe vacuum level can damage the high quality ceramic windows. In this thesis, an Experimental Physics and Industrial Control System (EPICS) controlled RF conditioning system for the SNS RF Test Facility (RFTF) has been presented. Various RF and control instruments are integrated through the EPICS system on Linux platform to measure and to control the vacuum and the RF power while monitoring electron emission and unwanted arcing during the conditioning. Monitoring arcing at the window and flow and temperature of cooling water in high power RF load and ceramic window is necessary to interlock the RF not to have any kind of undesirable operation condition. The interlock system has been designed by using the Programmable Logic Controller (PLC) and an RF switch with microseconds response time. Usually the whole conditioning process takes several days, so it is necessary to get the flexibility to control, monitor, and archive the system operation remotely along with good upgradeability. To get these advantages in EPICS, VXI/VME based Input and Output Controller (IOC)s are used for controlling and monitoring the RF conditioning system. This thesis summarizes all the hardware and software design strategies, provides the results obtained so far at room temperature and describes the future research scope.

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Chapter I

Introduction

1.1 Background

Radio Frequency (RF) Linear Accelerators (Linac) have been accelerating the electrons or ions up to an energy level of several hundred GeVs through accelerating RF cavities. To supply the energy to the charged particle beam a large amount of RF power needs to be coupled into the accelerating cavity structure. High power klystron amplifiers are widely used for the generation of the required RF power for the accelerator. Furthermore, waveguides and couplers are used to supply the RF power from the klystron to the cavities. The accelerating cavities and the klystron amplifiers maintain vacuum inside their structures, while the waveguides and couplers' airside pressures are typically that of the ambient environment. RF windows are used in the waveguides to separate the atmospheric pressure from the vacuum in the accelerator and the vacuum of the klystron. Ceramic windows are mostly used to pass large amounts of RF power with minimal loss. RF windows can usually be constructed in a hollow waveguide or a coaxial transmission line for both normal-conducting and superconducting cavities. Figure 1.1 shows a simplified diagram of the RF power transmission from the klystron to the accelerator.

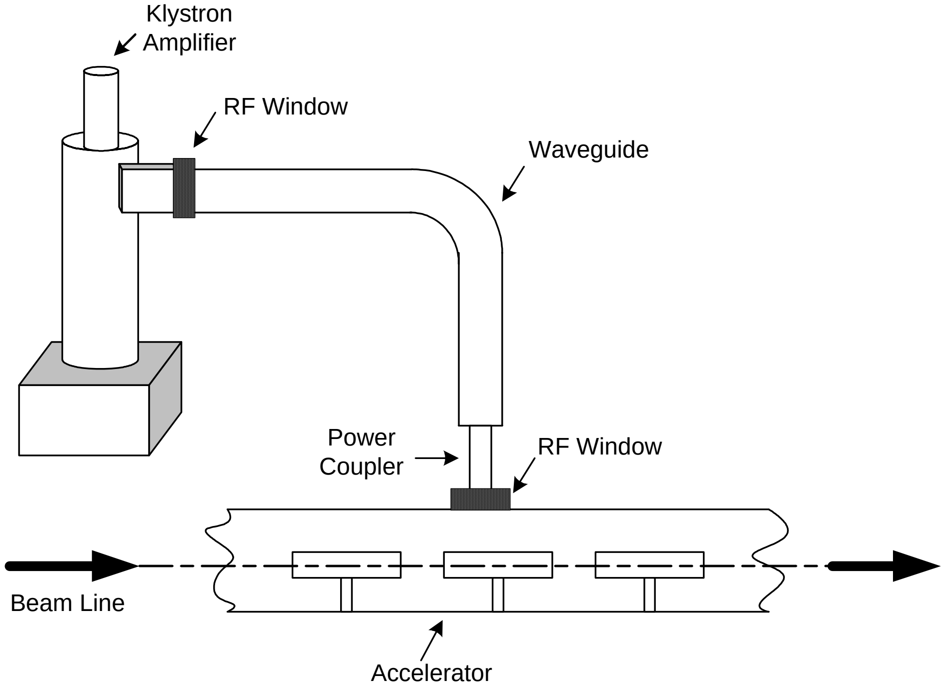


Figure 1.1: RF power transmission from the klystron to the accelerator.

Since the accelerating cavities operate under very high vacuum it is clear that the RF windows are very important to maintain the high vacuum and to transfer the high RF power. However, it is well known that these RF windows are the most likely part of an input power coupler to suffer catastrophic failure with window cracking or metal sputtering. This failure mostly occurs due to the severe arcing inside the structure when high RF power is applied prematurely under poor vacuum. Window failure may occur due to thermal stress and slight degradations in window RF performance may result due to large temperature gradients. It is been known that the RF windows can be conditioned with high RF power to the maximum performance before assembled to the clean accelerating cavities or klystron cavities. If proper conditioning under well-controlled conditions is omitted, the windows can be permanently damaged. Figure 1.2 shows an RF window for the rectangular waveguide designed by Thomson Electron Devices [1].

1.2 Problem Statement

RF conditioning of the windows is one of the most important tasks to be done before placing it to the cavities. A number of research laboratories are working on in this field to develop a reliable conditioning system. Three important needs are identified for the RF conditioning process: first, the need for a high speed interlocking system, which can interlock the RF power as fast as possible during the arcing and other abnormal situation to avoid the damage of the RF windows; second, the need for a fully automated conditioning control system, with less human operations; and third, the need for conditioning and archiving test data with remote connectivity.

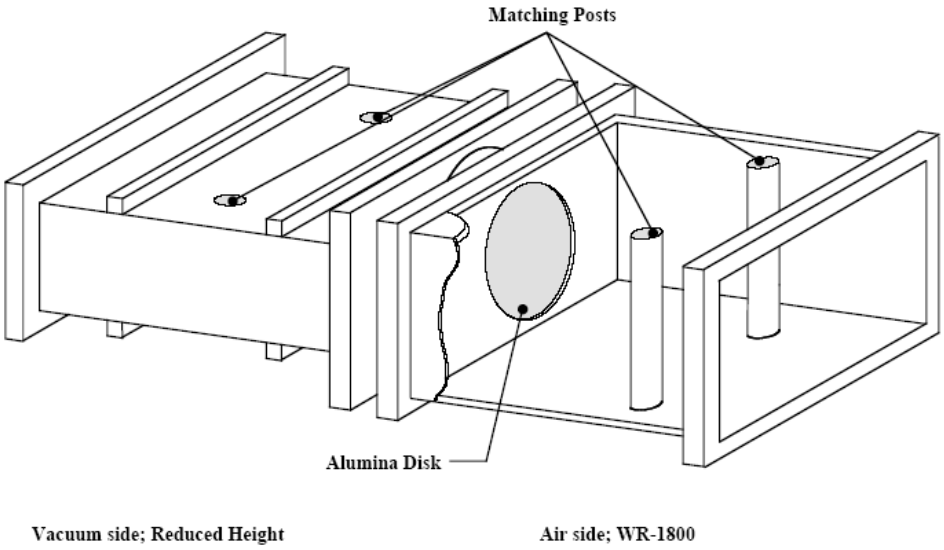


Figure 1.2: A schematic of a RF waveguide window [1].

EPICS was originally developed by Los Alamos National Laboratory (LANL) and Argonne National Laboratory (ANL) jointly in early 90's [30]. It is a set of software components and tools that application developers use to build distributed control system for Particle Accelerators, Large Experiments and major Telescopes. Such distributed control systems typically comprise tens or even hundreds of computers, PLCs, Instruments and Devices networked together to allow communication between them and to provide control and feedback of the various parts of the device from a central control room, or even remotely over the internet. All big laboratories in USA and other countries such as Australia, Japan, Germany, and UK are using EPICS to control their large machines. Now-a-days many private companies are also using EPICS for its flexibility and reliability and open source features. This is the reason to develop the RF conditioning system that can be EPICS based and integrated to the main control system of the SNS.

1.3 Research Objectives

The objectives of the current research are – (i) to study the existing RF conditioning processes and to define the problems, (ii) to design a reliable RF conditioning system using available resources, (iii) to implement the conditioning process with hardware and to select and setup all the instruments, (iv) to implement a complete control software in EPICS environment with good operator interfaces and remote control ability, (v) to evaluate the performance of the designed RF conditioning system for the RF windows.

1.4 Outline of the Thesis

The research described in this thesis seeks to develop a new RF conditioning system to process the RF windows. The design, development, operation, tests and analysis of the proposed RF conditioning system have been presented in six chapters. Chapter I discusses the background of the RF conditioning process and also current research trends.

Chapter II presents an overview of the SNS project in ORNL, basic descriptions of the Linac, Superconducting cavities and Power couplers. This chapter also describes the techniques for the RF conditioning process and presents the current research in this field.

In Chapter III, the description of the proposed RF conditioning system and hardware design approaches has been given. This chapter also presents the basic operation, setup and wiring of some key instruments.

Chapter IV presents the design and development of the control system software in EPICS for the RF conditioning process. The description of the basic software tools, which has been used to automate the RF conditioning process, has been presented also.

Chapter V provides the operation, results and analysis of the proposed RF conditioning system.

The conclusions of the thesis are drawn in Chapter VI and some recommendations for the future research works are discussed.

At the end, a list of references is attached which has been used for designing the proposed RF conditioning process and the vita of the author has been attached also.

Chapter II

Literature Review

This chapter presents the overview of the Spallation Neutron Source (SNS) project in Oak Ridge National Laboratory (ORNL) and it also provides the basic description of the Linear Accelerator (Linac), superconducting cavity, and power couplers used in this project. Furthermore, the definition, description and the need of the RF Conditioning Process are given at the last section of this chapter.

2.1 Spallation Neutron Source (SNS)

As neutrons has no charge, so they can be penetrated more deeply into materials than X-rays, light, or electrons and thus revealed the bulk structures and properties of materials. The superior ability of neutrons to determine where atoms are and how they move make them an important tool for physics, chemistry, biology, materials science, and engineering. So, the future research in these fields is depending on a high quality neutron source. The neutron sources are mainly two types – such as reactor-based, which supplies steady state or continuous sources of neutrons and accelerator-based, which is the source for pulsed neutrons. For many research problems of interest, having neutrons available in a series of intense pulses is better than having a continuous neutron source. Accelerators can produce neutron pulses with a much higher intensity than that available from continuous sources. SNS is a new, accelerator-based science facility that will provide neutron beams with up to ten times more intensity than any other such source in the world. SNS is being designed and constructed by a partnership of six U.S. Department of Energy (DOE) national laboratories (Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos, and Oak Ridge). ORNL in Tennessee is responsible for the civil construction, project management, design integration, and ultimately for operating the SNS. The other participating laboratories are responsible for design and construction of major technical subsystems that make up the facility [2].

The basic theory behind the SNS is - when a high-energy proton bombards a heavy atomic nucleus, such as mercury then some of the neutrons are "spalled," or knocked out, in a nuclear reaction process called spallation. Other neutrons are "boiled off" as the bombarded nucleus heats up. It's something like throwing a baseball at a bucket of balls, resulting in a few being immediately ejected and many more bouncing around and falling out. For every proton striking the nucleus, 20 to 30 neutrons are expelled. In the SNS project, negatively charged hydrogen ions (H^-), each of which consists of a proton orbited by two electrons, are produced by an ion source. These ions are injected into a linear accelerator, which accelerates them to very high energies. The ions are passed through a foil, which strips off each ion's two electrons, converting it to a proton. The protons pass into a ring where they accumulate in bunches. Each bunch of protons is released from the ring as a pulse. The high-energy proton pulses strike a heavy-metal target, which is a container of liquid mercury. Corresponding pulses of neutrons freed by the spallation process will be slowed down in a moderator and guided through beam lines to areas containing special instruments. Neutrons of different energies can be extracted and be used in a wide variety of experiments [3].

The map of the SNS Project has been shown in the Figure 2.1. In the Front End building H^- ions has been produced and sent it to the Linac Tunnel for the acceleration. Klystron building contains all the klystron amplifiers and other RF power sources for the Linac. After accumulating all the ions in the Ring they have been sent to the Target building for the production of neutrons. The Linac is mainly responsible for the acceleration of the neutrons and this is energized by the RF power. This thesis has been focused on the RF Conditioning Process of the window/couplers, which are the part of this Linac. The next section of this chapter describes how Linac accelerates the ions, general description of the Linac and basic structure and operation of the SNS Linac.

Figure 2.1: Spallation neutron source (SNS) in ORNL [2].

2.2 Linear Accelerator (Linac)

In 1927, R. Wideroe demonstrated the first RF linear accelerator at Aachen, Germany. He showed that electrons could be accelerated through a tube by applying a RF voltage to separated sections of the tube so that the electrons felt an accelerating electric field when they passed the gap. If it was arranged so that the electrons arrived at the next gap at the right phase of the RF voltage, they would be accelerated again, getting double the energy they would have gotten from just the application of the maximum field of the RF. The linear particle accelerator is a long linear array of accelerating "cells" powered by a RF source in the megawatt power range and in the gigahertz frequency range. [4].

A main advantage of the Linac is its capability for producing high-energy, high-intensity charged-particle beams of high beam quality, where high beam quality can be related to a capacity for producing a small beam diameter and small energy spread. Other attractive characteristics of the Linac include the following points.

- Strong focusing can easily be provided to confine a high-intensity beam.
- Because the beam travels in a straight line, so power loss is minimum.
- Injection and extraction of the beam are simple.
- The Linac can be operated at any duty factor, all the way to 100% duty or a continuous wave, which results in acceleration of beams with high average current.

2.2.1 Overview of Linac Structures

In Figure 2.2, a simplified block diagram shows a Linac structure with accelerating cavities and focusing magnets, and supplied with electromagnetic energy by an RF Power system. Beam is injected from a DC injector system. A vacuum system is required for good beam transmission. Electrical power is used primarily by the RF power system. A cooling system (Water for normal-conducting Linacs and liquid helium for superconducting Linacs) removes the heat generated by the resistive-wall losses. Because the Linac uses a sinusoidally varying electric field for acceleration, particles can either gain or lose energy, depending on the beam phase relative to the crest of the wave. To provide efficient acceleration for all the particles, the beam must be bunched as shown in Figure 2.3. The bunches may be separated longitudinally by one or more RF periods [5].

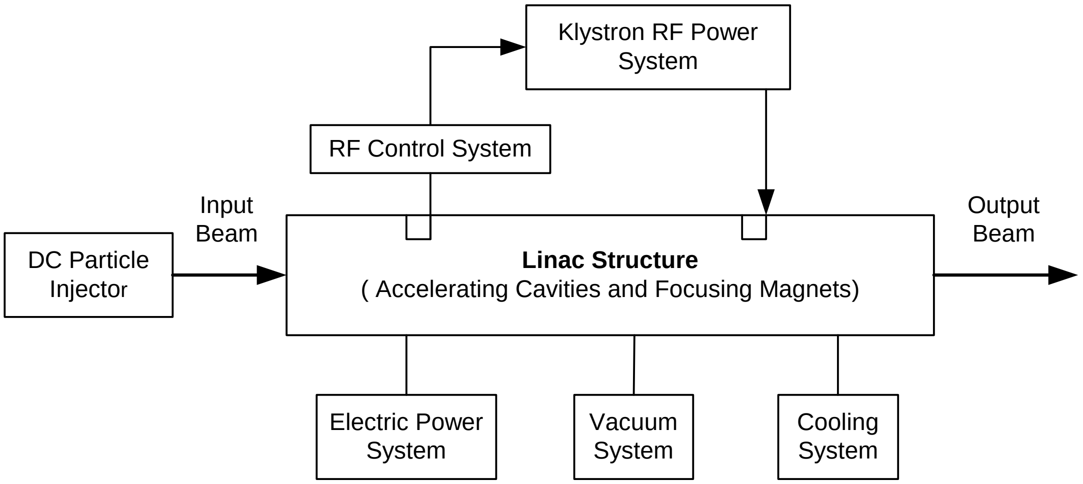


Figure 2.2: Simplified block diagram of Linac [5].

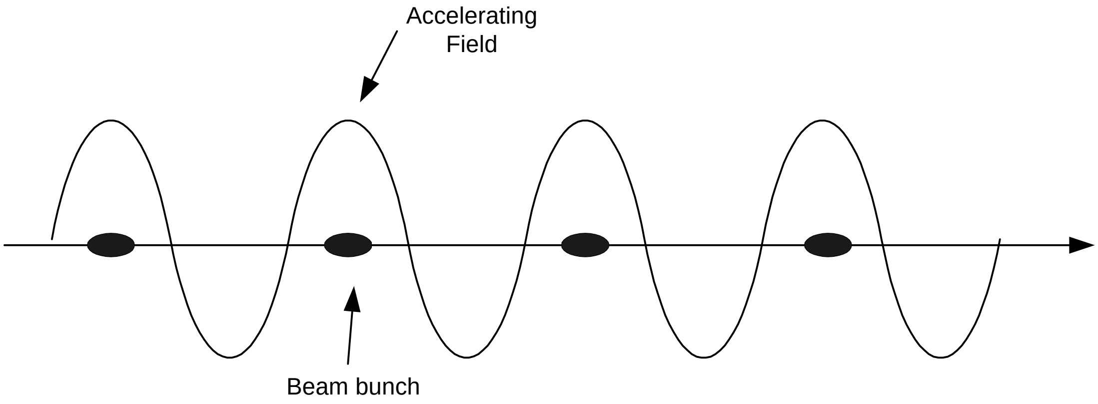


Figure 2.3: Beam bunches in an RF Linac [5].

It has been already mentioned that the RF power is used to accelerate the particles. To understand how this power is used to accelerate the particles, let's assume a simple pillbox cavity with a single accelerating gap. In the Figure 2.4 the electric field within this pillbox has been shown. The length of the arrows represents the magnitude of the electric field, and it has been shown that the largest electric field is in the center of the cavity. The electric fields oscillate at the resonance frequency of the structure. The force (in Newtons) on the particle is represented by Equation 2.1.

$$F=qE \tag{2.1}$$

Where, q is the charge of the particle, 1.60×10^{-19} Coulombs and E is the electric field in the cavity. Electric field is sinusoidally varying and a forward force accelerating the particles along the Linac at the positive peak. However, when the electric field is negative, the particles are traveling in a shielded 'drift' space between cavities so the

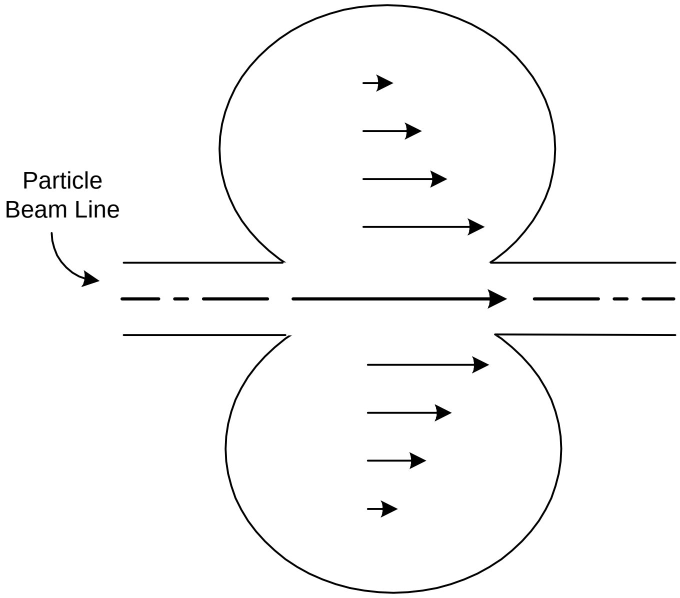


Figure 2.4: The electric field in a pillbox cavity [6].

particles are never be exposed to a reverse force. Thus, the particles are accelerated by the oscillating electric fields and absorb energy from the cavities. RF power is coupled into the accelerating structures to accelerate the particles and it is generated by klystrons. Electromagnetic RF waves are transmitted to the accelerator through waveguides and couplers. One klystron provides the RF power to a small section of the accelerating structure; therefore many klystrons are required to provide the RF power to a large scale accelerator [6].

2.2.2 SNS Linac

The SNS Linac is a pulsed proton Linac and the RF system of this Linac must support a 1 msec beam pulse at up to a 60 Hz repetition rate. The Linac consists of Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL), Coupled Cavity Linac (CCL), a medium

(β=0.61) and high beta (β=0.81) superconducting RF (SRF) Linac, and two buncher cavities for transporting beam to the ring . Pulsed RF Power is supplied to the RFQ and DTL by using seven 2.5 MW Klystrons of 402.5 MHz. These accelerating structures are followed by four CCL cavities. A single, pulsed, 5 MW, 805 MHz klystron provides power to each CCL cavity. The power from the klystron is split, and the cavity is driven through two RF windows. The CCL cavities are followed by eighty-one SRF cavities and each cavity is driven by a pulsed 550 kW klystron [7]. Figure 2.5 shows the SNS Linac with RF system partitioning. The SRF Linac section occupies more than two third of the Linac. Although all vacuum components require high quality cleaning and preparation, the SRF component are subject to even more stringent requirements.

The primary function of the front-end system is to produce a beam of H^- ions to be injected into the Linac at 2.5 M eV. Here the RFQ bunches and captures a beam injected

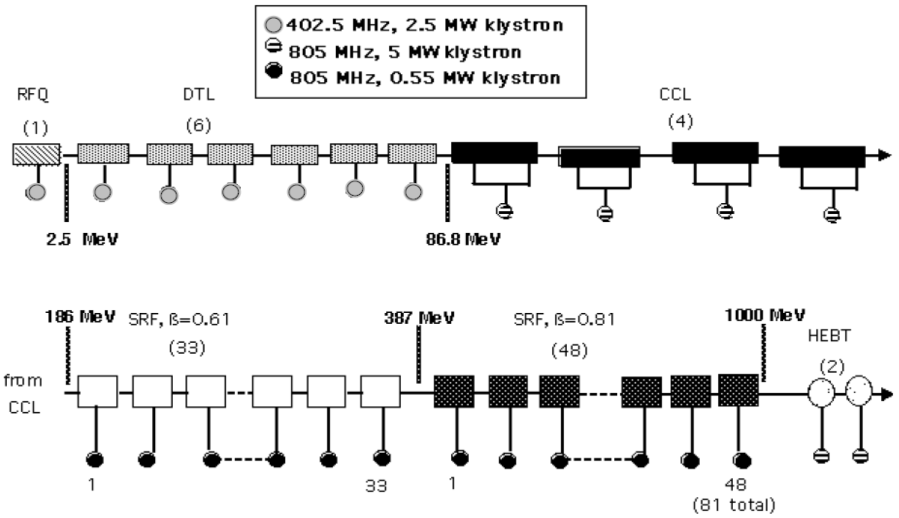


Figure 2.5: SNS Linac with RF system partitioning [7].

from the ion source, and then accelerates the beam to high-enough energies for injection into the DTL. The overall result is a significant increase in the focusing strength at low velocities, which enables acceleration of higher-current beams in Linac. In the SNS Linac, DTL accelerates the beam from 2.5 to 25 MeV, CCL further accelerates beam to 186 MeV, and SRF accelerates beam to its final value of 1.0 GeV [8].

SNS Linac is operated by pulsed RF power instead of Continuous Wave (CW) operation. If the accelerated beam current is small, most of the power in CW operation is not delivered to the beam but is dissipated in the structure walls. Instead, if the accelerator is operated pulsed, and the current per RF bucket is increased while maintaining the same average beam current, a larger fractional power is delivered to the beam and the efficiency is improved. The whole system is computer controlled with EPICS environment.

2.3 Superconducting RF Cavities in the Linac

An electromagnetic cavity resonating at a microwave frequency, which imparts energy to the charged particles, is a key component of the modern particle accelerators. Consider first the case of a charged particle moving at nearly the velocity (v) of light ($\beta = v/c \cong 1$). As it traverses the half-wavelength ($\lambda/2$) accelerating gap in half a RF period, it sees the electric field pointing in the same direction for continuous acceleration. Figure 2.6(a) to (c) shows the evolution of the typical superconducting accelerating structure for a velocity-of-light particle [9].

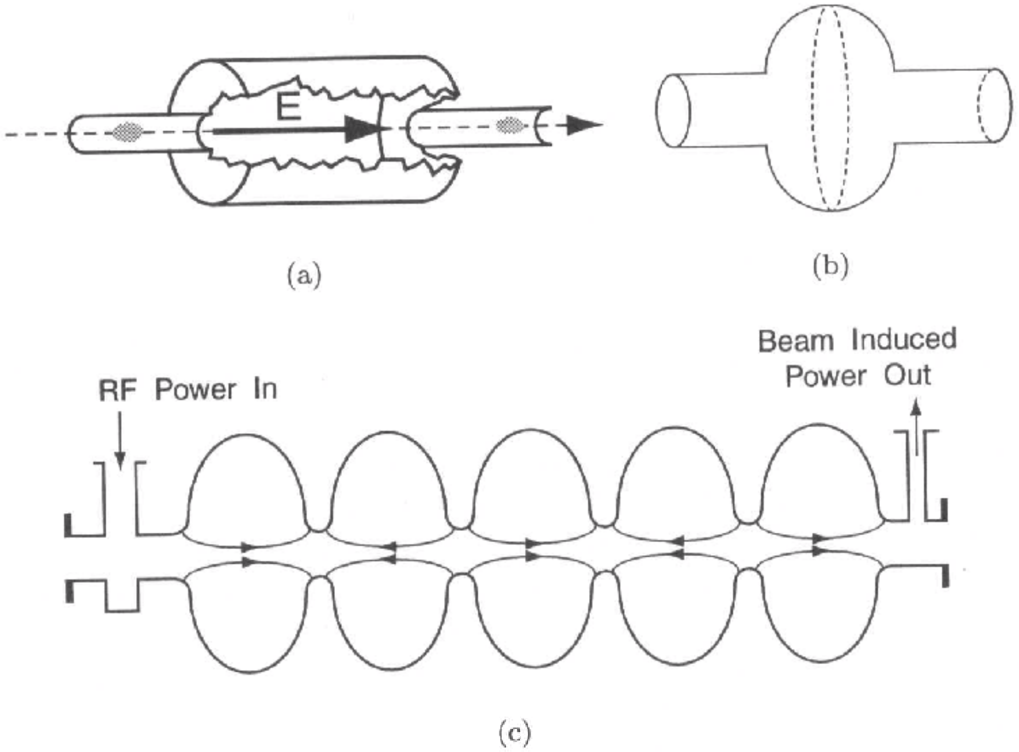


Figure 2.6: Evolution of typical SRF cavities for the accelerators.

(a) A cylindrical pill-box cavity, with beam holes and beam pipes, resonating in the TM_{010} mode for which the electric field is maximum on the axis. (b) As cylindrical shape is unsuitable for superconducting cavities because of multipacting so, rounding the curved wall eliminates the problem. (c) The typical accelerating structures consist of a chain of cavities. There are ports on the beam tubes to bring RF power in to establish the fields and to deliver power to the beam. There are additional ports for removing power induced by the beam in the higher-order resonant modes of the cavity [9].

The two most salient characteristics of a superconducting accelerating cavity are its high average accelerating field, E_{acc}, and the high quality factor Q_0, which is the intrinsic Q of the resonant cavity. The quality factor is a universal figure of merit for resonators and is defined in the usual manner as the ratio of the energy stored in the cavity (U) to energy lost (P_c) in one RF period. It measures the number of oscillations a resonator will go through before dissipating its stored energy. The Q_0 depends on the microwave surface resistance of the metal. Since the power dissipation in the walls of a copper structure is substantial so the superconductivity is highly desirable to build the cavities. The microwave surface resistance of a superconductor is typically five orders of magnitude lower than that of copper, and therefore the Q_0 is five orders of magnitude higher.

In the SNS project, two types of superconducting cavities with geometrical β values of β=0.61 and β=0.81 are being used. Both types consist of six cells made from high purity niobium and feature one High Order Mode (HOM) coupler of the TESLA type on each beam pipe and a port for a high power coaxial input coupler. E_{acc}=10.1 MV/m and Q=$5x10^9$ at 2.1 K for the β=0.61 and E_{acc}=12.5 MV/m and Q=$5x10^9$ at 2.1 K for the β=0.81 [10]. In the Figure 2.7 the image of the SNS superconducting RF cavities has been shown.

2.4 Input Power Couplers

The main function of the input power coupler is to transfer RF power from the klystron to the cavity and hence the beam. There are two major varieties of input couplers, such as hollow waveguide and coaxial. The basic structures of these couplers have been shown in

(a) β=0.61 (b) β=0.81

Figure 2.7: Image of the SNS superconducting RF cavities [10].

the Figures 2.8 to 2.9. In a waveguide coupler the electric field of the RF wave couples to the field of the waveguide propagating in the TE_{01} mode. The length of the shorted waveguide stub on the other side of the beam tube can be adjusted to maximize the damping of the unwanted higher order modes (HOMs). However, the coaxial coupler is compact and suitable for low frequency cavities, and medium HOM power extraction. Here the TM_{011} HOM electric field coupled to a coaxial antenna coupler despite a loop can be used at the end of the center conductor to couple to the magnetic field. The detail description of these couplers can be found in [9]. The following discussions will focus on the coaxial coupler windows to be used with superconducting accelerating cavities.

2.4.1 Coupler Windows

The primary role of the window is to protect the cavity vacuum from the atmospheric pressure and to transfer the RF power with a very low loss. Usually a warm window, located far from the superconducting cavity, is used for the high average power application. On the other hand, for the low average power applications (less than 10 kW), when window associated RF losses are less of a concern, and then the cold window,

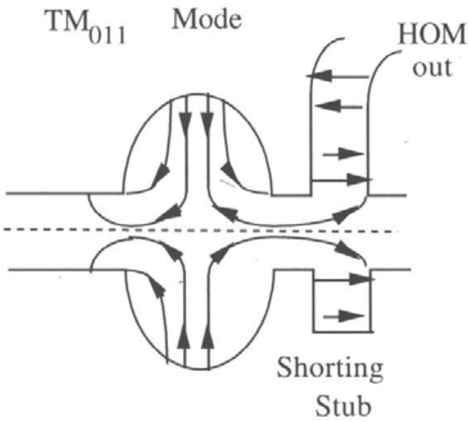


Figure 2.8: Basic structure of a hollow waveguide coupler [9].

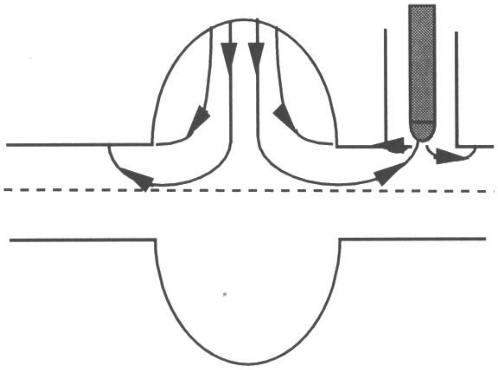


Figure 2.9: Basic structure of a coaxial coupler [9].

located near the cavity, is used. Low thermal conductivity, availability in the needed purity and sizes has been made alumina the best material for constructing windows [9].

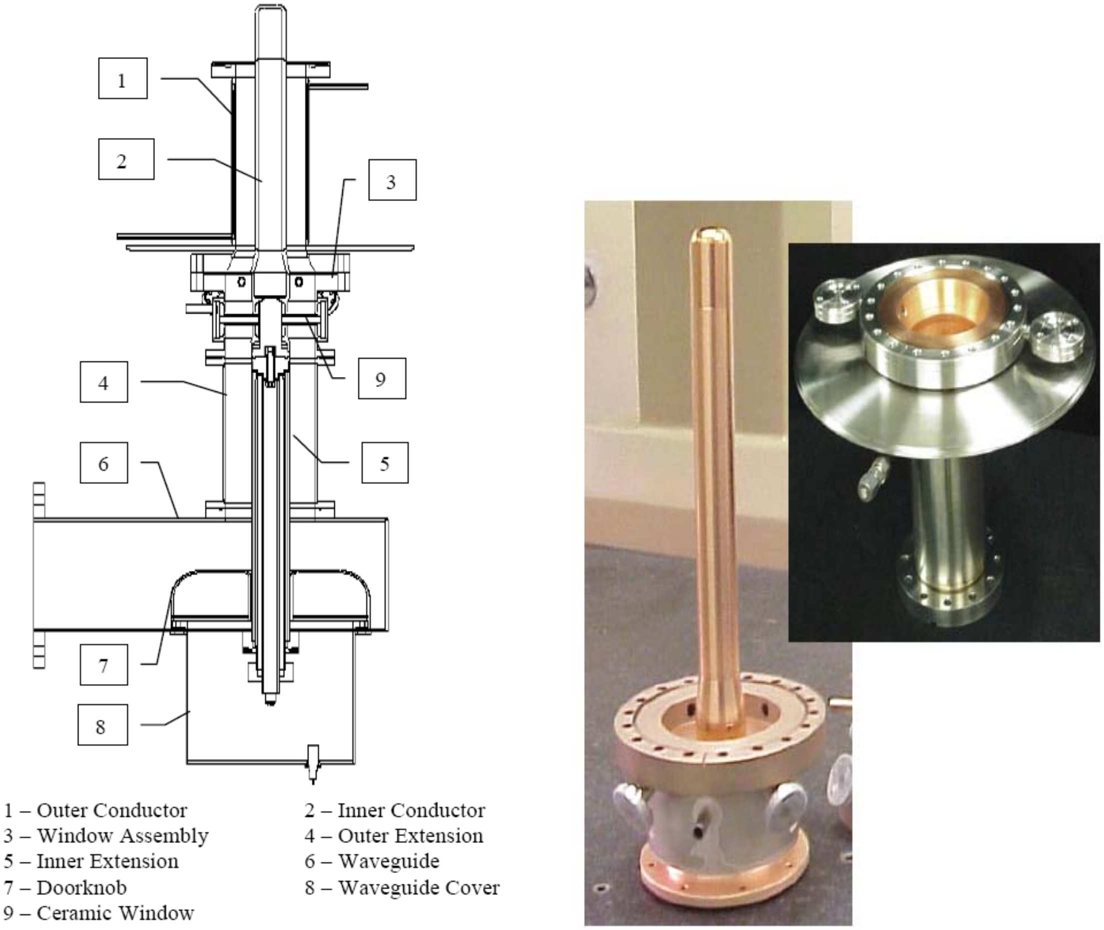
2.4.2 Characteristics of the SNS Coupler

Each of the 805 MHz superconducting cavities of the SNS is powered via a coaxial Fundamental Power Coupler (FPC) with a 50 Ω characteristic impedance and a warm planar alumina window. The couplers must be able to withstand at least the peak power delivered by the SNS klystrons, 550 kW for a 1.3-msec pulse length at a repetition rate of 60 pulses per seconds (pps) [11]. The parameters of the SNS superconducting cavity couplers are shown in the Table 2.1 and Figure 2.10 shows the schematic and the image of the SNS power coupler.

The coupler includes the antenna, coaxial window which is a planar annular disk-type made of 95% alumina ceramic, and the waveguide to coaxial transition which has a

Table 2.1: Required parameters of the SNS coupler [11].

Parameter	Operation	Processing
Q_{ext}	about 7×10^5	NA
Impedance	50 Ω	
Peak power	550 kW	1 MW max
Pulse length	1.3 ms	1.3 + ms
Repetition rate	60 pps	60 pps max
Average power	48 kW	60 kW
Bias	± 2.5 kV	± 2.5 kV



(a) Schematic of the FPC

(b) Window and inner conductor; and outer conductor

Figure 2.10: SNS input power coupler [11].

doorknob type impedance matching structure. The transition alone must have good impedance matching to assure best performance when integrated with the ceramic window. Even a small mechanical change inside the structure can result in a significant change in the RF performance. The planar alumina window includes impedance-matching elements as well as TiN anti-multipacting coating.

Multipacting in the coaxial line and at the window can produce window limitations and failures [See more discussion in the section 2.5]. Extensive simulations have been performed to study the multipacting behavior of the FPC and the levels and locations have been predicted [12]. The FPC includes the possibility of biasing the inner conductor via a capacitor gap between the doorknob and the inner conductor itself at variable voltages between –2.5 and + 2.5 kV. The gap is filled with Kapton® foil, which is capable of withstanding the biasing voltage [13]. So, this capacitor helps to control the multipacting during high power conditioning and operation.

2.5 High Power RF Conditioning

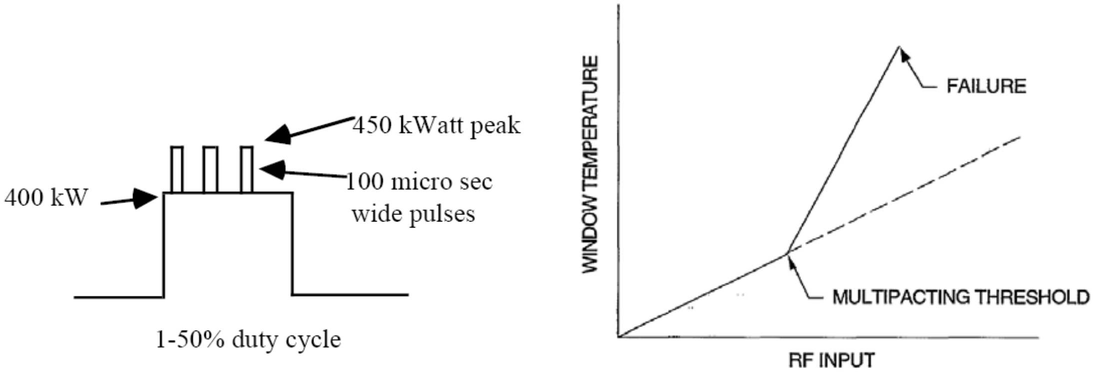
Multipacting in RF structures is a resonant process with secondary electron emission phenomenon in which a large number of electrons build up and collide with structure walls, leading to a large temperature rise and eventually causes the thermal breakdown. At present, multipacting still damages many types of RF vacuum structures, such as low-β cavities, couplers, transmission lines, and RF windows [9]. This also plays the most important role for damaging the RF windows in the couplers and limiting the maximum peak power by arcing. In addition to multipacting, sometimes the dielectric stresses, thermal induced stresses, material imperfections, and ohmic losses also damages the windows. However, many of these phenomena may be the result of multipacting. It has been known that proper high power conditioning can remove the multipacting and associated problems.

So, it is essential for the RF window to be conditioned with high RF power before attaching the assembly to the cavity. The goals of the conditioning are to increase the amount of the RF power through the window while maintaining good vacuum and limiting arcs. During conditioning it is important to ensure nonlinear heating, a sign of multipacting, does not occur. The goal is achieved by slowly increasing the RF power while waiting for the vacuum pressure to decrease and minimize the arc rate [6].

2.5.1 Conditioning Methods from the Literature

A conditioning method called ‘tickle processing’ has been developed by Pisharody, et. al. [14]. In this method, 100 micro seconds pulses of 20-50kW are superimposed on top of the primary RF pulses, at 1% to 50% duty cycle, as shown in the Figure 2.11(a). This shorter RF pulses limit the vacuum bursts and thus improve the efficiency of the processing by achieving much swifter progress. By using this method, a power level of 300 kW CW was obtained in 20 hours at Jefferson Laboratory (JLAB). The highest power achieved was 430 kW at 33% duty cycle.

The description of another conditioning method has been found in [15] and [16]. This



(a) Tickle processing at 400kW [14]

(b) Window temperature vs. input power [15] [16].

Figure 2.11: RF conditioning process in the literatures.

process involves recording the window temperature as a function of RF input. The window temperature should increase linearly with RF input. A nonlinear increase is an indication of multipacting. Figure 2.11(b) shows the graph of this process. The multipacting and nonlinear heating may lead to the failure of the window.

Thomas Jefferson National Accelerator Facility (TJNAF) has developed another RF conditioning system described in [17] to condition the SNS FPCs. The control system has been designed by using the software LabView from the National Instruments and the testing was started in the JLAB with both traveling and standing wave modes. This system was transferred to ORNL and has been used extensively to condition all the SNS FPCs.

2.5.2 Brief description of the RF conditioning

It has been already mentioned that the RF windows of the couplers should be conditioned before placing it for the real operation. Otherwise, it can be damaged due to the severe arcing with poor vacuum for the premature application of the RF power. In this section, we have summarized the conditioning process, requirements and some results from the previous literatures.

The typical setup for the conditioning process is to place two window assemblies back-to-back so that the RF power enters the vacuum waveguide region through one coupler and then exits through the second coupler to a room temperature matched load. Since it is difficult to maintain atmospheric pressure on one side and vacuum on the other side of a window, this back-to-back construction is useful. Usually the lower sections of these couplers are connected with a bridge waveguide and for the smooth transmission of the power and to maintain the vacuum. Another advantage of this setup is, two couplers can be conditioned together, which will save money and time. Figure 2.12 shows a schematic of this setup.

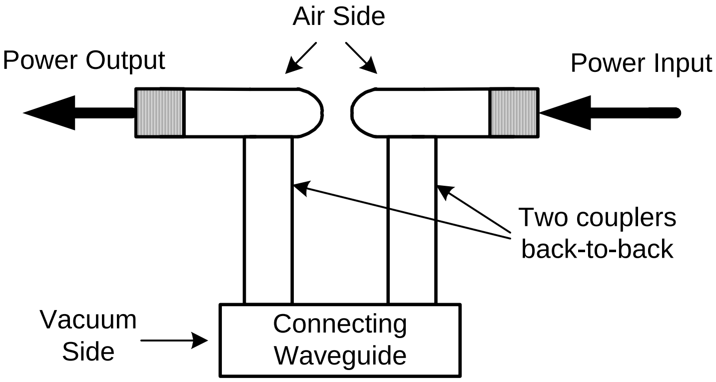


Figure 2.12: Typical setup for the RF conditioning.

To avoid any kind of catastrophic window failure it is necessary to use the fast interlock during the conditioning stage as well as during normal operation. As an example, if arcing occurs during the conditioning process then the input RF power should be turned off as fast as possible to protect the window. So, it is important to have an electron pickup probe and arc sensors close to the window to diagnose and protect against arcing and multipacting. Moreover, if the vacuum level near the window degrades to above 5×10^{-7} mBar, then the RF should be turned off fast to avoid sputtering and coating the ceramic with metal or removing the anti-multifactor coating from the window.

During the conditioning the power level should be increased slowly to get the best results. Furthermore, the vacuum system should have a high pumping capacity for effective conditioning in a reasonable time. Vacuum pressure is usually increased with electron activity, glow discharge, and arcing. Moreover, during these events some outgasing of various molecules, such as H_2, CO_2, N_2, has been observed. However, pulsed power conditioning with short pulses is very useful to limit the outgasing and to limit the duration of the arc.

The RF window should be conditioned both for the traveling wave mode and the standing wave mode. In traveling wave mode one end of the waveguide, which transfers power, is connected with a matched load and during the standing wave mode a short should replace this load. After conditioning, the windows should be kept under vacuum until the coupler is ready for attachment to the cavity.

Figure 2.13 and 2.14 shows the KEK/Toshiba experience in conditioning cylindrical and coaxial windows, and JLAB experience in conditioning the SNS FPCs, respectively.

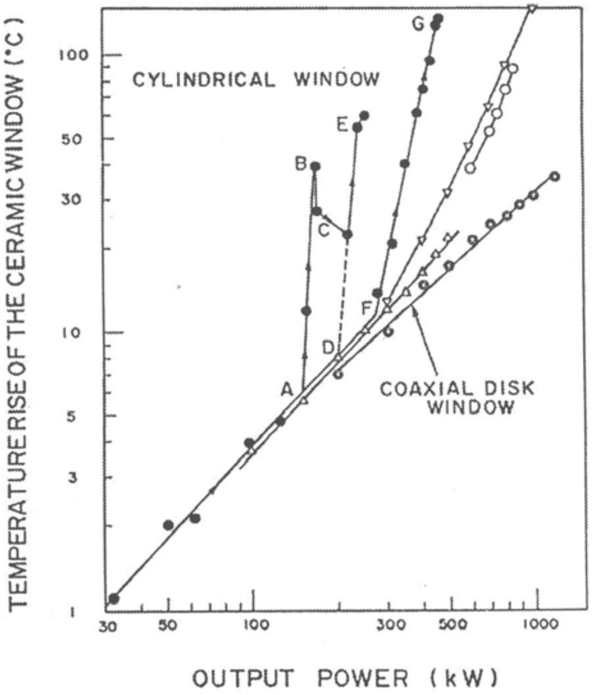


Figure 2.13: KEK/Toshiba experience in conditioning [18].

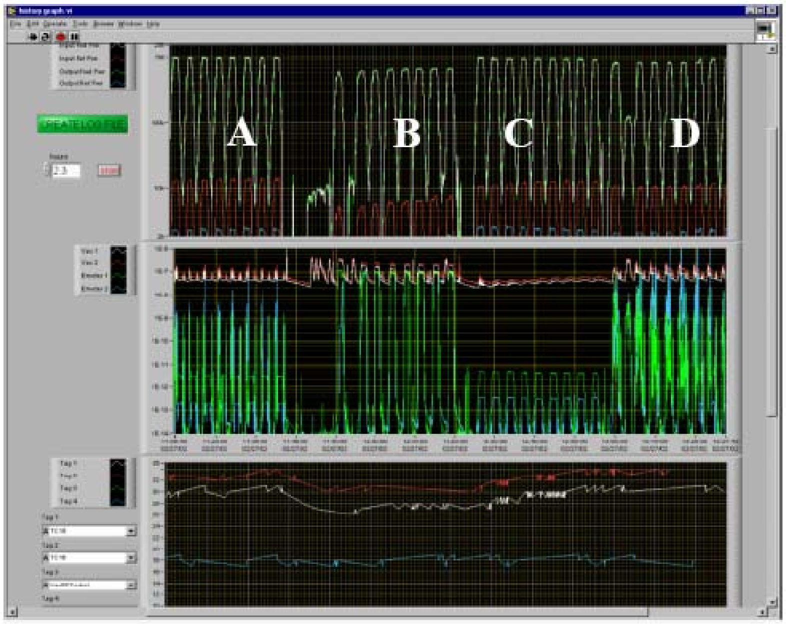


Figure 2.14: JLAB conditioning experience with SNS FPCs [17].

Chapter III

Design and Instrumental Setup

In this chapter the complete instrumental setup, block diagrams, description of the overall RF conditioning process, and hardware design approaches are given. We have also provided the operational basics, programming structures, cabling and wiring of some key instruments.

3.1 List of Instruments and Devices

RF Conditioning process is a combination of many state-of-the-art instruments and devices from various companies. All of these devices can be operated remotely via RS-232, RS-485, GPIB, or ETHERNET communications. The main devices for the RF conditioning process are –

1. Programmable Logic Controller (PLC)
2. Vacuum Gauge Controller (VGC)
3. Cold Cathode Gauges (CCG)
4. Signal Generator
5. Peak Power Meter
6. Vacuum Pumping Cart
7. Arc Detector
8. Fast RF Interlock Switch

9. Transmitter Control for the Klystron Amplifier

10. High Voltage Converter Modulator (HVCM)

11. Water Cooling System

12. VXI/ VME based Input Output Controllers (IOC)
    - Vacuum IOC
    - Klystron IOC
    - RF Power IOC

The description and parameters settings of some key instruments and devices, which fall into the scope of this thesis, are given in the section 3.3.

3.2 Overall System Diagram

The overall block diagram of the RF Conditioning System is shown in Figure 3.1. During the RF conditioning process of high power vacuum components such as cavities, couplers, windows, etc, it is necessary to monitor the vacuum quality, arcing, and forward and reflected RF power levels. The amplified RF from the klystron amplifier will be transmitted to the devices under processing through the waveguide transmission line. Between the klystron and a power coupler there are directional couplers to monitor the power signal (In this thesis, couplers are used as the devices under conditioning). The RF power will be transmitted to another power coupler through a connecting waveguide and finally reach the termination that is a water load for traveling wave processing or an adjustable short for standing wave processing. Another directional coupler is used between the load and the power coupler for monitoring the

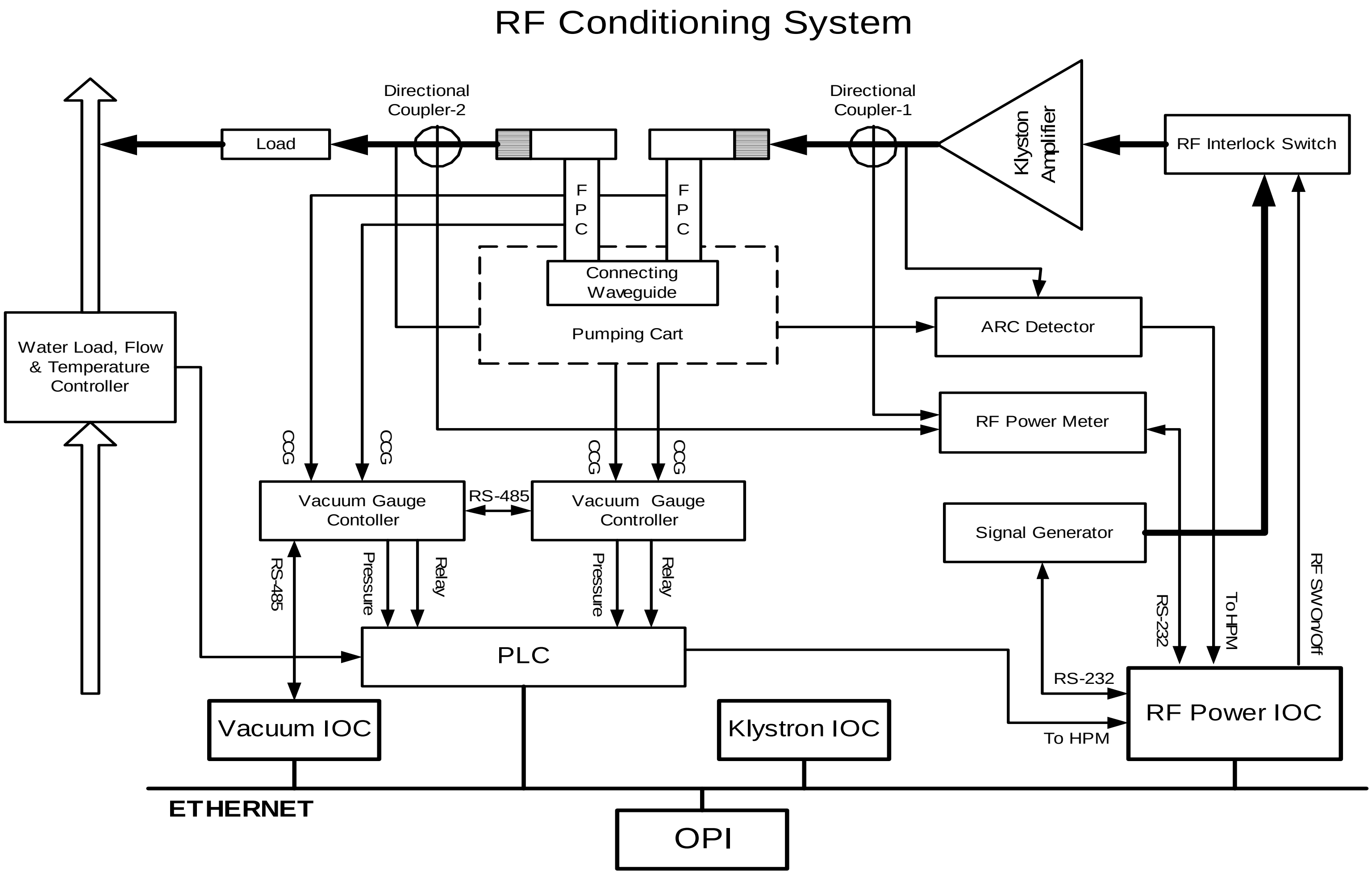


Figure 3.1: Block diagram of the RF conditioning system [19].

RF matching at the termination. Two RF power meters each with two channels are connected to the RF power IOC through RS-232 to measure the forward and reflected power levels at the input and the output ports of the couplers.

Two cold cathode gauges (CCG) are used to monitor the vacuum inside each coupler and another two were used to continuously monitoring the pumping cart's vacuum. These four gauges are connected to two MKS vacuum gauge controllers (VGC). Every VGC has five modules – analog module, which gives the pressure reading in raw analog format, relay module, which gives the relay status, communication module helps to communicate with other device, and two CCG controller modules measure the pressure. Analog modules and relay modules are directly connected to the PLC to supply the pressure and relay status information, respectively. If vacuum pressure crosses the predefined upper limit then the PLC will send a RF off request signal to the High Power Module (HPM) of RF power IOC.

The RF power is increased or decreased to maintain the optimum vacuum while monitoring the vacuum. The IOC will shut down the RF interlock switch within a few microseconds during any kind of abnormal situation. So, PLC is used for continuously monitoring the vacuum level and other auxiliary systems like water load, flow and temperature conditions. Communication modules of VGC are also connected with the vacuum IOC through RS-485 for controlling the VGC's remotely. RS-485 communication is little bit slower than the raw analog and digital communication. But if the vacuum pressure goes above the predefined maximum upper limit then the RF power needs to be shut down as fast as possible; that’s why the raw analog and relay signals are directly connected to the analog input module and digital input module of the PLC for taking the necessary actions. The RS-485 communication is used to configure the VGCs remotely.

Signal generator is connected to the RF power IOC through RS-232 connection. The output of this signal generator goes to the RF interlock switch and delivered to the driver amplifier. If the IOC gives the permission to pass the signal then the switch passes the signal to the driver for klystron amplifier. A separate IOC controls the klystron amplifier and the modulator. An arc detector is used on each coupler to detect the arc during the RF conditioning process and it is connected to the HPM of the RF power IOC. RF power IOC shuts down the switch to interlock as soon as any arc occurs. So HPM is the main module to get all the signals for controlling the RF interlock switch.

Since all IOCs and PLC are connected through Ethernet, it is possible to control and monitor the conditioning process from the main control room and anywhere else if desired. EPICS is to be used in the whole RF conditioning control system for more robust, flexible, but simple process control and monitoring. Main Operator Interface (OPI) screen was designed in such a way that the operator can observe the status of any instrument, set the parameters, control every step of the conditioning process, and archive the data and results.

3.3 Description of the Instruments and Devices

In this section the basic operation, brief description, configuration and parameter settings of some key instruments are given.

3.3.1 Programmable Logic Controller (PLC)

Allen Bradley's ControlLogix® PLC is used in the RF conditioning process for the high-speed interlocking of RF signal to avoid any kind of abnormal situation. ControlLogix® is a new standard for the PLC to provide the high performance for the application requires in an easy-to-use environment [20]. The ControlLogix® system provides sequential, process, motion, and drive control together with communications and state-of-the-art Input Output (I/O) in a small, cost-competitive package. The system is modular, so we can design, build, and modify it efficiently -with significant savings in training and engineering. A simple ControlLogix® system consists of a stand-alone controller and I/O modules in a single chassis. ControlLogix® 1756 model is used for our application. In Figure 3.2 the basic parts of the ControlLogix® PLC has been shown. The basic parts of a ControlLogix® PLC system are –

a. **I/O Chassis:** The ControlLogix® system is a modular system which requires an I/O chassis to hold the various modules. Any module can be placed into any slot.
b. **Power Supply:** Power Supply module is the main source of power for all the modules and it provides 1.2V, 3.3V, 5V and 24V dc power directly to the chassis backplane.

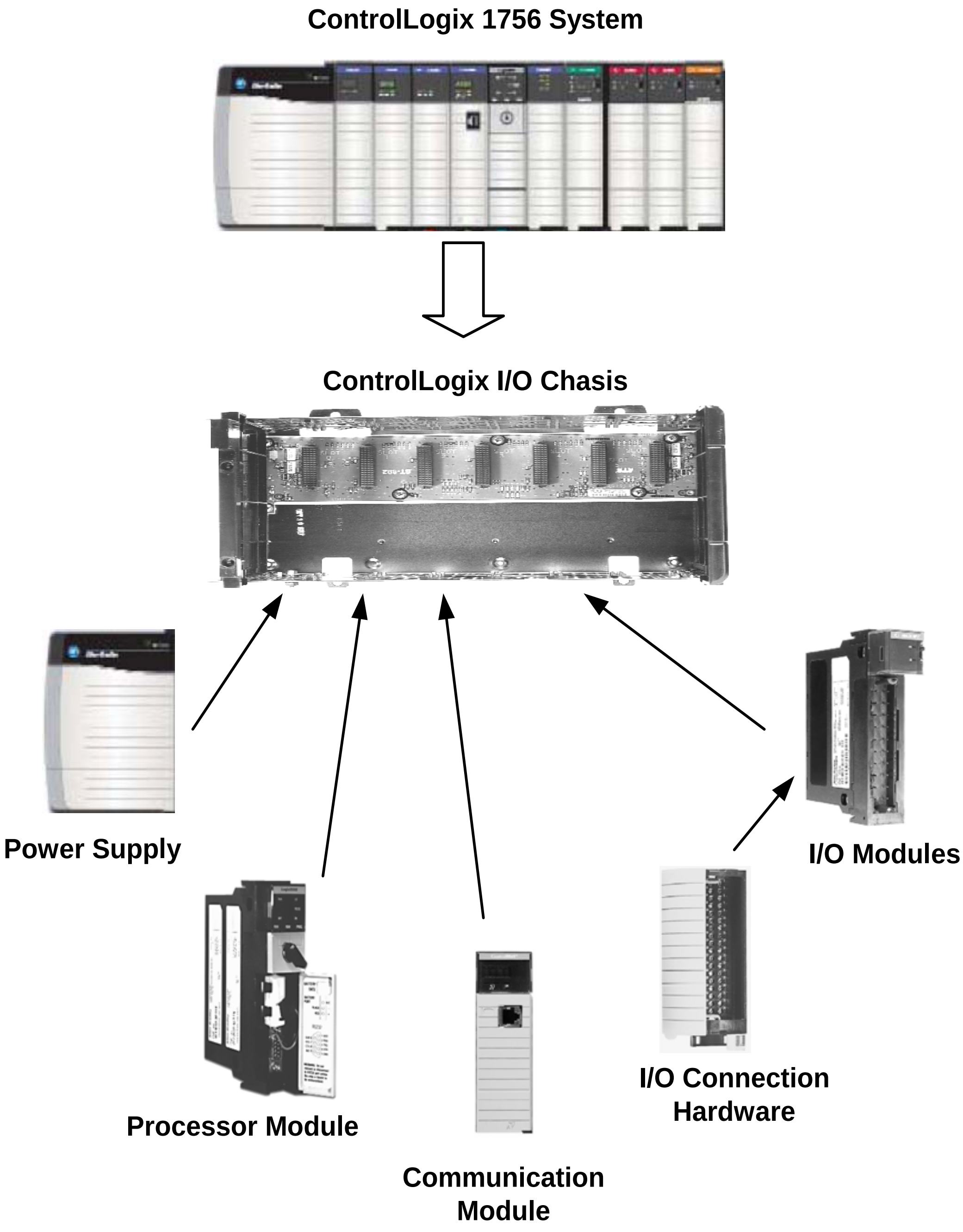


Figure 3.2: Controllogix® 1756 system modules [20].

c. **Processor Module:** Process input values to control outputs.

d. **Communication Modules:** In the local chassis, it provides a port for communication to computers, other PLC processors, or I/O adapters at other locations. In an I/O chassis remote from the processor, it provides a port for interfacing I/O modules on the backplane to a processor at another location.

e. **I/O Modules:** Converts input-circuit signals to backplane levels and converts backplane signals to output circuit levels.

f. **I/O Connection Hardware:** Connection hardware that plugs onto the front of the I/O modules to provide connection points for I/O circuits. It is also called RTB (Removable Terminal Block).

ControlLogix® wiring system has mainly two parts –

a. **Interface Modules (IFMs):** Interface Modules are mounted on DIN rails provide the output terminal blocks for the I/O module. Use the IFMs with the pre-wired cables that match the I/O module to the interface module.

b. **I/O-module-ready cables.** One end of this pre-wired cable assembly is an RTB that plugs into the front of the I/O module. The other end has individually color-coded conductors that connect to a standard terminal block.

Figure 3.3 provides the wiring modules and peripherals for the I/O connection, Table 3.1 lists the PLC modules which has been used for the RF conditioning process and Figure 3.4 shows the pictures of the interface modules and pre-wired cable.

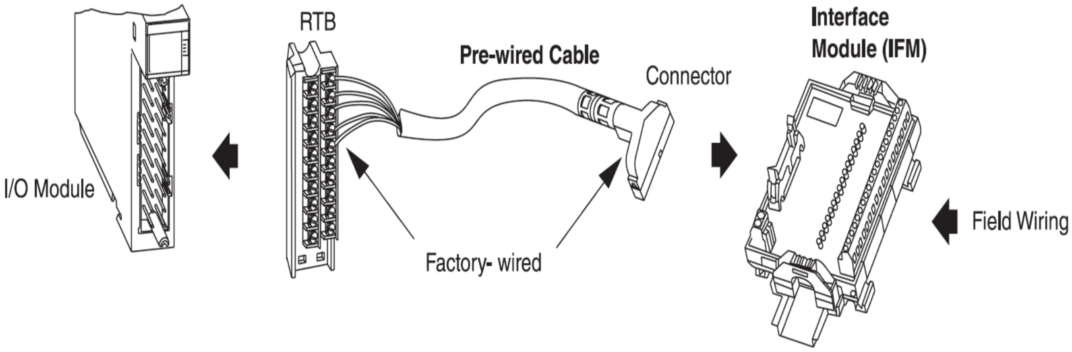


Figure 3.3: Controllogix® 1756 wiring systems [21].

Table 3.1: List of PLC modules for the RF conditioning process [22].

	Main Module	Interface Module	Pre-wired Cable
1	1756A10 ControlLogix Chassis	-	-
2	1756-PA72/B PLC System Power supply	-	-
3	1756-L1M1 PLC Processor	-	-
4	1756-ENET/B Ethernet Interface module	-	-
5	1756-IB32 Digital Input Module	1492-IFM40D24	1492-CABLE010-Z
6	1756-OB16D/A Digital DC Output Module (24V-Diagnostic)	1492-IFM40DS24-4	1492-CABLE007-Y
7	1756-IF8/A (0-10v) Analog Input Module	1492-AIFM8-3	1492-ACABLE005-TB (Single ended current)
8	1756-OF4/A (4-20mA) Analog Output Module	1492-AIFM4-3	1492-ACABLE005-VB (Single Ended Current)

(a) Pre-Wired Cable (b) 1492-IFM40D24 (c) 1492-IFM40DS24-4

(d) 1492-AIFM4-3 (e) 1492-AIFM8-3

Figure 3.4: Pre-wired cable and interface modules [21].

3.3.2 Vacuum Gauge Controller (VGC)

A multi-sensor high vacuum system from the MKS Instruments has been used for continuously monitoring the vacuum inside the coupler and vacuum pumping system. We have chosen MKS 937A for our purpose [23]. This system operates as many as five sensors simultaneously and supports Cold-Cathode (CC), standard-pirani, convection-pirani and thermocouple sensors and capacitance manometer together to measure pressure from as high as 10,000 Torr down to ultra high vacuum. In Figure 3.5 the image of a MKS Vacuum Gauge Controller has been shown. This VGC has several modules and these should be configured before placing it for vacuum measurement. The description of those modules are given follows-

Figure 3.5: MKS 937A vacuum gauge controller [24].

a. **Analog Module-** This module provides the analog output signals for each sensor from the analog 25-pin D-type Connector and this signal can be sent to a data acquisition system. These includes buffered, logarithmic, and combination logarithmic output. We have used the logarithmic pressure output for our purposes and this output ranges from 0 to 10 V and is scaled to 0.6 V per decade of pressure change and are updated each 50 to 250 ms depending on the number of sensors in the controller. The pressure P in Torr as a function of voltage V in volts can be calculated by using the following equation-

$$P = 10^{\left(\frac{V}{0.6} - 12\right)}$$

b. **Communication Module-** This module gives the facility to control front panel functions or read pressure and other information remotely by direct computer communication. It supports RS-232 and RS-485 communication protocol. Each module has two 9-pin D-connectors. One is male and another is female. As we have two VGC in our system, so we have used the RS-485 protocol, which allows multiple devices to be connected on the same wires to a host computer [25].

c. **Set Points-** VGC has five adjustable relay set points. These relays are tripped if the vacuum exceeds any predefined set point values and the status of the relays can be accessible through the rear 15-pin D-connectors in accessory module. The controller also includes additional protection and control set points to turn a cold cathode sensor off at higher pressures.
d. **Sensor Modules-** The VGC system has three slots labeled, CC, A and B for placing different sensor modules with different configurations. For measuring the pressures in coupler and pumping cart each VGC have two cold cathode modules in slot CC and A respectively.

There are some DIP Switches (SW) and jumpers in communication modules and analog modules for setting up different parameters and configuring the VGC for different sensors. Table 3.2 and Table 3.3 show the settings of Communication Module (COM) and Analog Module respectively.

3.3.3 Signal Generator

Signal Generator plays an important role for the RF conditioning process. Rhode & Schwarz® general-purpose signal generator SML-01 model has been chosen for it’s wide frequency range, large variety of modulation functions and high reliability – at an

Table 3.2: Switch settings for the communication modules.

SW-1 Settings in COM module			
Bit Rate	*Parity*	*Switch*	*Position*
19,200	Even	4	On
		1,2,3	Off
Connection Type		*Switch*	*Position*
Normal RS-485, Multidrop Protocol		5, 6	On
SW-3 Settings in COM module			
Address for VGC -001		*Switch*	*Position*
ASCII: A, Digital: 1000001		2,3,4,5,6	On
		1,7	Off
Address for VGC -002		*Switch*	*Position*
ASCII: B, Digital: 1000010		1,3,4,5,6	On
		2,7	Off

Table 3.3: Switch settings for the analog module.

Parameters	*Settings*	*Switch*	*Position*
Pressure Units	mBar	1	On
		2	Off
Control/Combination Sensor Channels	For Slot CC-B1	3	Off
	For Slot A –B2	4	On
Line Frequency	60 Hz	5	Off
CC Sensor Delay	3 Sec	6	Off
Configuration	N/A	7	Off

affordable price [26]. The image of this Signal Generator is given in the Figure 3.6.

3.3.4 Power Meter

It is necessary to continuously monitor the RF peak power in the coupler at the time of its conditioning process. Agilent® E4417A EPM-P series power meters have been selected for the RF conditioning process [28]. These meters measure the peak powers by using Agilent® model E9322A sensors. Each of the meters has two channels for measuring the power. Since the conditioning process needs four channels to measure the forward and reflected powers at the input and output of the couplers, two power meters has been used with four sensors. In Figure 3.7 the image of the power meter and sensors are given.

Zeroing and Calibrating:

Before taking any measurements each power meter should be calibrated and zeroed with a reference power. Zeroing adjusts the Power Meter for a zero power reading with no power applied to the power sensor. Calibration sets the gain of each power meter channel and sensor combination using a 50 MHz 1 mW (0 dBm) signal. Power meter's POWER REF is giving an output of this type of signal. So before taking the measurements each

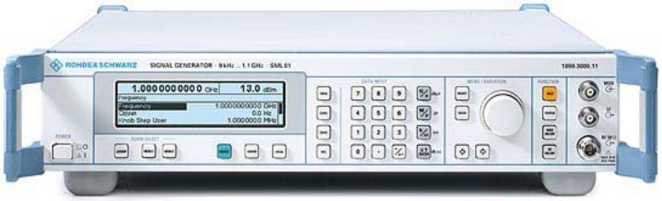


Figure 3.6: Rhode & Schwarz® SML-01 signal generator [27].

(a) E4417A EPM-P Series Power Meter (b) E9322A Series Peak Power Sensors

Figure 3.7: Peak power meter and sensors [29].

channel with a sensor should be connected to this POWER REF output and ‘Zero+Cal’ button should be pressed for zeroing and calibrating the sensors.

3.4 Cabling and Wiring of the Instruments

The PLC which has been used for the RF conditioning system has four I/O modules, analog input module, analog output module, digital input module and digital output module. Currently analog output module is not being used and this has been placed for the future purposes. In this section the wiring and connection diagrams of the PLC modules, VGC modules and IOCs are given.

3.4.1 Accessory Module of VGC to Digital Input Module of PLC

The accessory module supplies the relay status information from the VGC and this module should be connected to the digital input module of the PLC. Since digital input module requires 24 volt input, a 24 volt DC voltage source has been used here to fulfill the requirement. The connection diagram between these two modules has been shown in

Figure 3.8. VGC-001 and VGC-002 are the vacuum gauge controllers for the Device Under Processing (DUP) and pumping cart respectively.

3.4.2 Analog Module of VGC to Analog Input Module of PLC

Analog module of the VGC gives the pressure reading of the CCGs in raw analog format and it has been connected to the analog input module of the PLC. PLC reads these raw pressure data, converts it to the digital value and supplies the pressure information to the vacuum IOC. Figure 3.9 shows the connections between the accessory module of VGC and the analog input module of PLC.

3.4.3 Digital Output Module of PLC to HPM

PLC has been programmed in such a way that it will continuously monitor the set points and pressure reading data from the VGCs and send the 24-volt signal to the HPM in RF power IOC. But if the PLC detects any fault during the RF processing then it will send no voltage to the HPM. So, digital output module of the PLC is used for sending the 24-volt OK signal to the HPM of RF power IOC. In Figure 3.10 connection diagram has been shown between these modules.

3.4.4 RS-485 Connections between VGC and Vacuum IOC

VGC's communication module can support both the RS-232 and RS-485 protocols. For the RF conditioning system RS-485 protocol has been chosen to communicate with the VGCs remotely. 8 channels UART Industry Pack (IP) IP-SI-8516 from the Hytec Electronics Ltd. has been used to support the RS-485 protocol and Hytec 8002 VME IP carrier board has been placed in the vacuum IOC to support this 8516 IP module. This IP

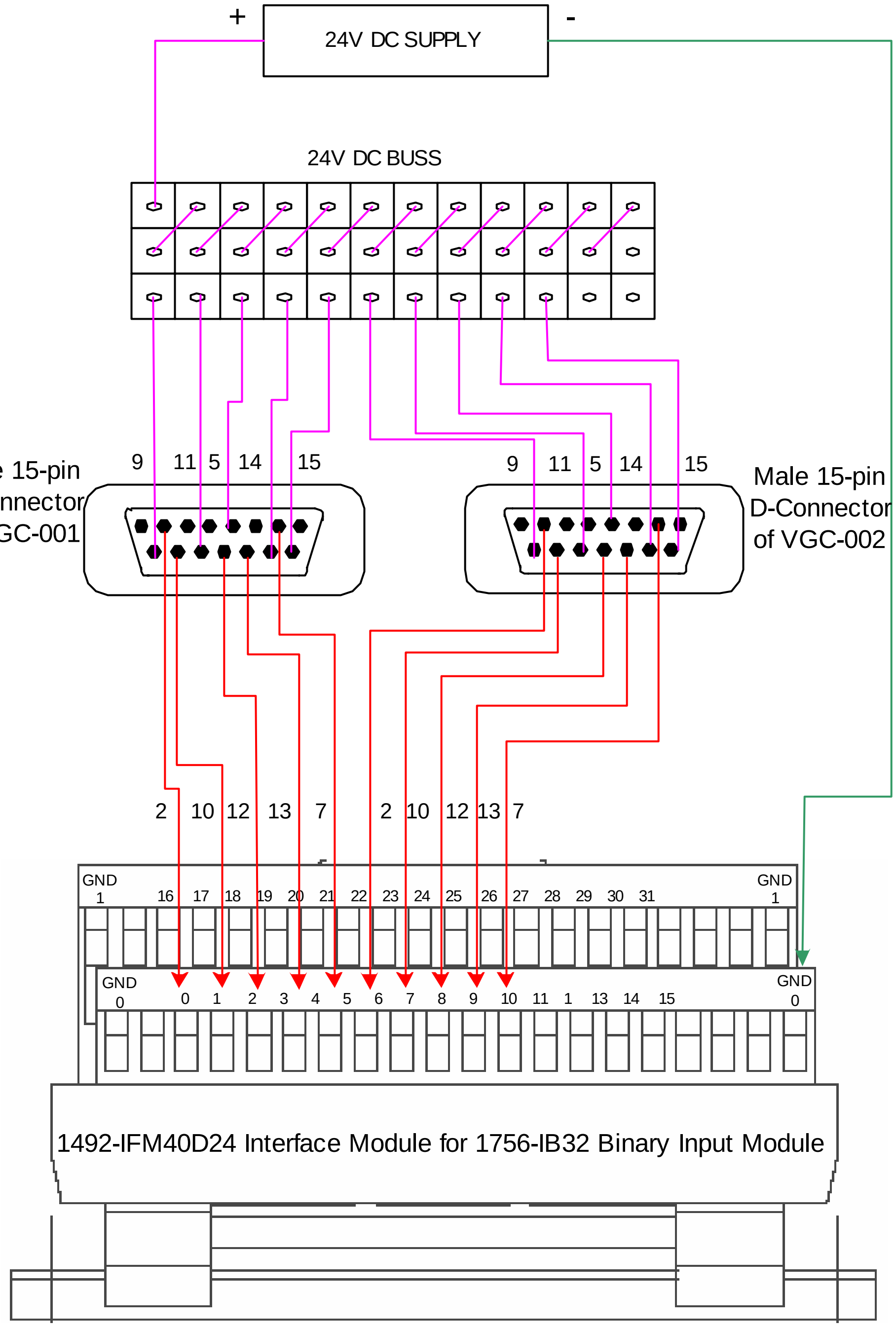


Figure 3.8: Connections between accessory module of VGC and digital input module of PLC.

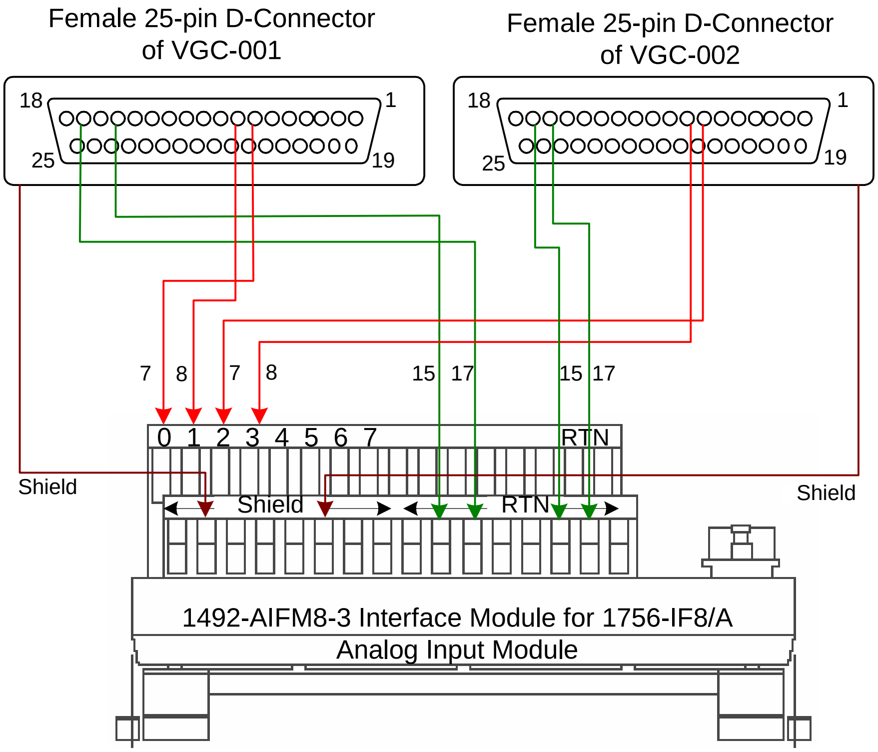


Figure 3.9: Connections between analog module of VGC and analog input module of PLC.

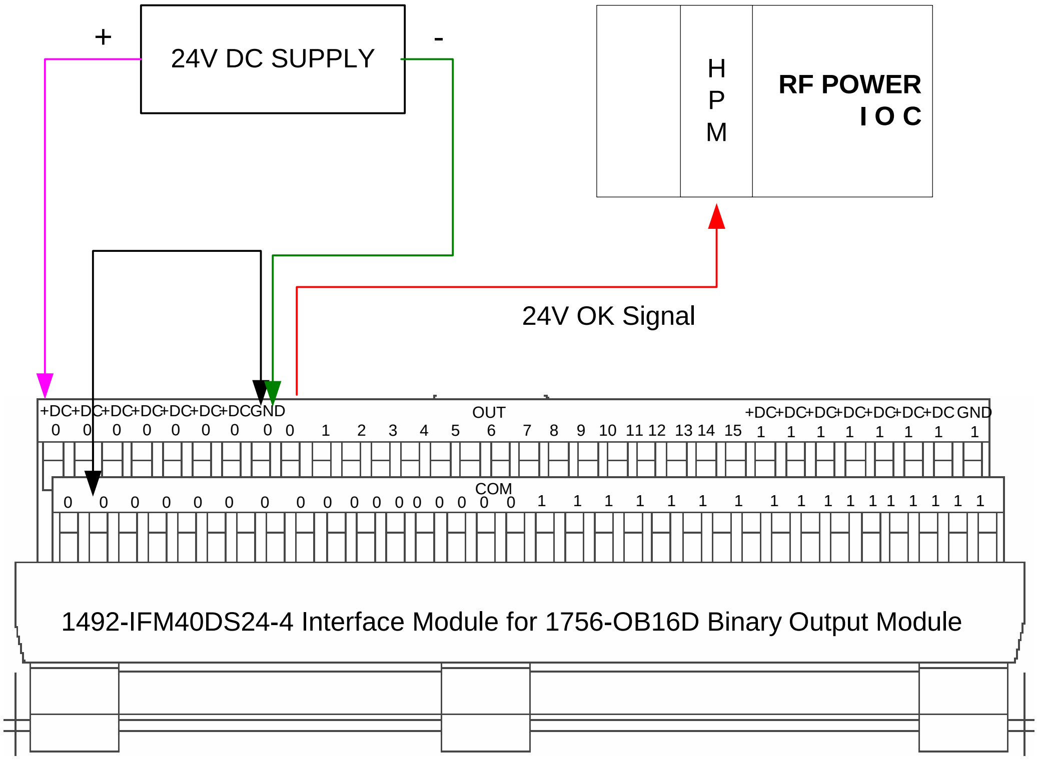


Figure 3.10: Connections between digital output module of PLC to the HPM of RF power IOC.

module is connected with a terminal board by a SCSI cable and connections has been made between the communication module of VGC and the Hytec terminal board. Two VGCs are connected by a daisy chain connection. Figure 3.11 shows all the necessary connections to communicate with the VGCs from the IOC by using RS-485 protocol.

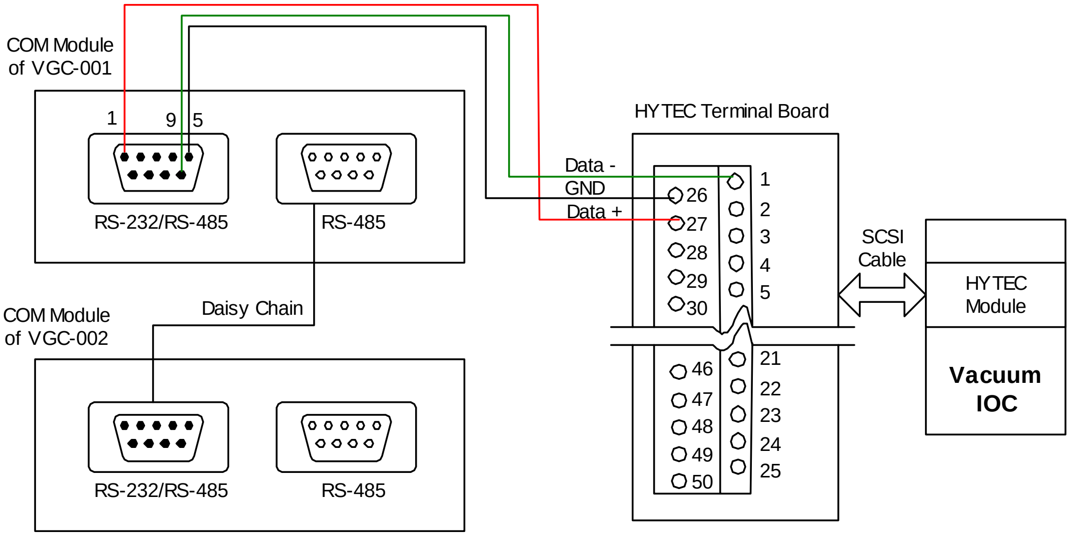


Figure 3.11: RS-485 connections between VGC and the vacuum IOC.

Chapter IV

Development of the Control System Software

To control the whole RF conditioning processing efficiently it is necessary to design the control system software by focusing on the following facts –

- The algorithm of the software should be flexible for the future upgradeability.
- It should be modular, so that the debugging can be done easily with less time.
- It should have a good Operator Interface (OPI).
- All the results and data should be archived for future analysis.

RF conditioning process has mainly two types of programming –

1. High-level programming based on Experimental Physics and Industrial Control System (EPICS) for the IOCs.
2. Low-level programming for the PLC.

This chapter presents the brief description of programming style of the EPICS and PLC. It also provides the step-by-step analysis of the RF conditioning process control system software's algorithm and PLC programming with the help of flow charts.

4.1 Experimental Physics and Industrial Control System (EPICS)

In this section some basic idea about the EPICS has been given. The detail description and the programming style of the EPICS can be found in [31]. The basic components of the EPICS are:

- **OPI**: Operator Interface. This is a workstation that can run various EPICS tools.
- **IOC**: Input/Output controller. This can be any platform that can support EPICS run time databases together with the other software components.
- **LAN**: Local Area Network. This is the communication network, which allows the IOCs and OPIs to communicate.

The Physical implementation of the EPICS is shown in Figure 4.1. EPICS provides a software component, channel access, which provides network transparent communication between a channel access client and an arbitrary number of channel access servers. The

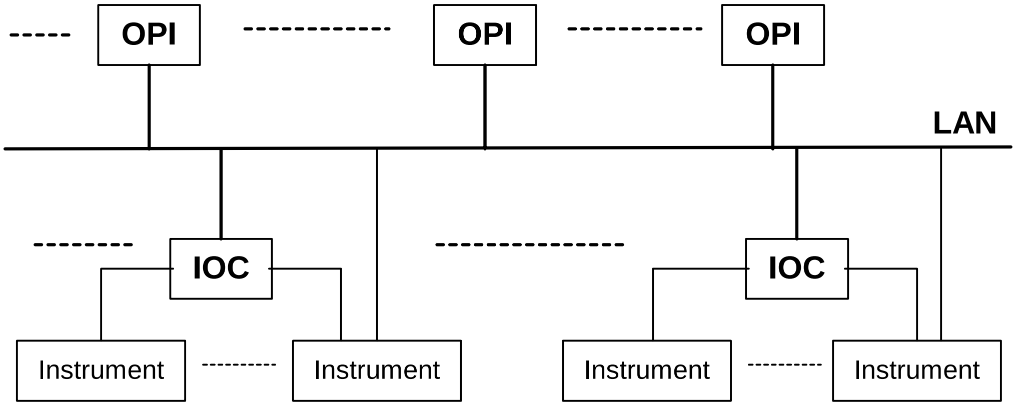


Figure 4.1: Physical structure of a control system based on EPICS.

descriptions and features of some key software components of EPICS which are used for the RF conditioning process are given in the following sections.

4.1.1 IOC Software Components

IOC can be various types but the most popular IOC is a single-board computer running the vxWorks real-time operating system and installed in a VME chassis. An IOC often performs input/output operations to attached hardware devices and associates the values of EPICS Process Variable (PV)s with the results of these input/output operations. An IOC can perform sequencing operations, closed-loop control and other computations.

IOC can be classified in to two depending on the run mode. 'Host-based' IOC runs in the same environment as which it was compiled. Sometimes this is called a 'Soft' IOC and this is a program like any other on the machine. It is possible to have many IOCs on a single machine. On the other hand 'Target' IOC runs in a different environment than where it was compiled. IOC boots from some medium (usually network) and it is the only program running on the machine. RF conditioning process uses the 'Target' IOC for controlling the instruments.

Many software components such as device support, device drivers, database, and sequencer are coming with the EPICS base or as an extension, which helps to control the instruments and devices connected with the IOC. Figure 4.2 shows the software components for the IOC in EPICS.

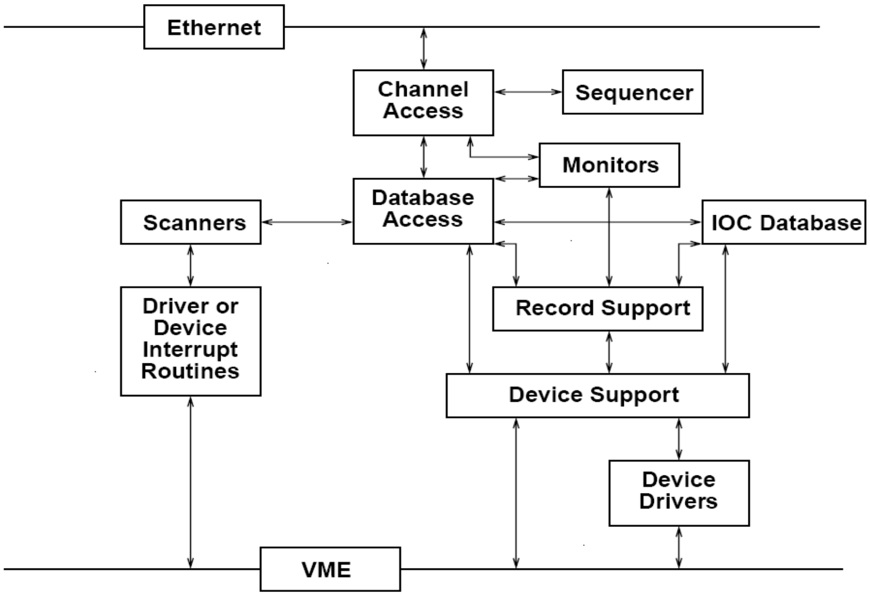


Figure 4.2: EPICS supplied software components for IOC [31].

Following sections describe the EPICS database and sequencer briefly.

EPICS Database:

EPICS control system may contain one or more IOCs and each IOC loads one or more databases telling it what to do and a database is a collection of records of various types and a record is an object with, a unique name, a behavior defined by its record type (class), controllable properties (fields), optional associated hardware I/O (device support), links to other records. Records are active; they can get or put data from other records or from hardware, perform calculations, and check values are in range and raise alarms, activate or disable other records, wait for hardware signals (interrupts). Record actions depend upon its record type and the settings of its fields and no action occurs unless a record is processed.

Sequencer:

Depending on the state of the control system sequencer can make decision for what to do next. It is used for calibration and initialization of the equipment, fault detection, and to control and monitor the whole system by using some predefined states in the program. State Notation Language (SNL) is the tool to write the sequencer program and State Notation Compiler (SNC) helps to compile it. SNL is a ‘C’ like language to facilitate programming of sequential operations [32]. Sequencer program can be compiled easily and it can be executed fast in the real-time environment. EPICS sequencer was developed by the Stanford Linear Accelerator Center (SLAC). Sequencer version 2.0.10 is being used extensively to control the RF conditioning process.

4.1.2 OPI Software Components

Extensible Display Manager (EDM):

Extensible Display Manager (EDM), developed by SNS/ORNL, is a tool to build and mange the displays for the control system [33]. It provides the ability to create and edit display content such as graphics, text, meters, sliders, buttons, plots, etc. and uses some facility such as EPICS channel access to execute the same content resulting in the dynamic presentation of live data.

Strip-Tool:

Strip-Tool is an application, which acquires data by channel access and plots it in real time as a strip chart. This is very useful for debugging controls applications and for monitoring data trends.

4.1.3 Other Software Components

Channel Archiver and Archive Viewer:

Channel archiver developed by LANL is a toolset for EPICS to archive the data and Java based archive viewer developed by SNS is used to view these archived data.

Visual Database Configuration Tool (VDCT):

VDCT, developed by Cosylab, is a very powerful tool to write and manage the EPICS databases graphically.

4.2 Designing the Control System

All the instruments, meters and devices connected with the IOCs are supplying the values of the requested parameters to the channels in the format of EPICS PVs. As described earlier EPICS databases are maintaining the link between these PVs and the instruments in the field through the IOCs. RF conditioning process constitutes several states with some predefined conditions and instructions. So supplied PVs from the instruments should be monitored continuously and depending on these real-time PV values the state of RF conditioning process has been determined. Then the process continues by following the conditions and instructions written in each state. The possible states during the RF conditioning process have been summarized below-

- Initialize: Starts the control program, initializes and calibrates instruments.
- Increase: Increases the RF power.
- Decrease: Decreases the RF power.

- Hold: Hold on the current RF power.
- Vacuum Upper Limit: Takes necessary actions when vacuum crosses the upper limit.
- Fault Detection: This state starts in any kind of abnormal situation.
- Ramp after Fault Detection: Starts the conditioning again after the fault diminishes.
- End: Finishes the conditioning process.

EPICS sequence program has been used to control and define the states. In this section each of the state has been described with the help of flow charts.

4.2.1 Initialize State

The main task of the sequence program is to control the RF power by analyzing the power and vacuum limits and the current values. When the program starts then it sets the RF power amplitude in the signal generator to the predefined RF lower limit. The values of some parameters have been defined also. These parameters are only used for the programming purposes. Then the sequencer monitors the RF permit signal from the RF power IOC, which controls the RF interlock switch. If the RF permit is ON then the sequencer jumps to the 'Increase' state otherwise it goes to the 'Fault Detection' state. Figure 4.3 shows the flow diagram of the 'Initialize' state.

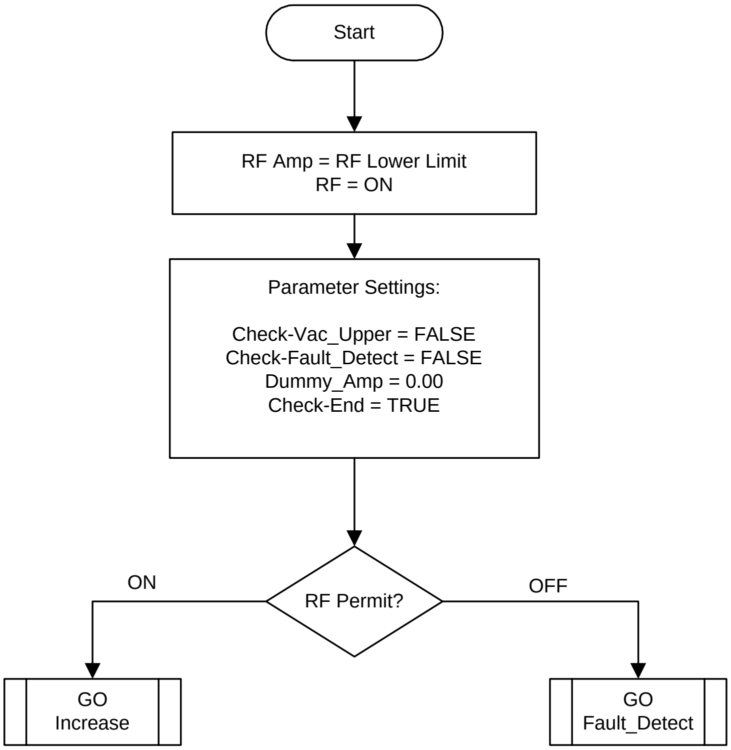


Figure 4.3: Initialize state.

4.2.2 Increase State

The main task of the 'Increase' state is to increase the RF power and the step of the increment can be defined by the variable 'RF Increment'. However, the sequencer jumps to the 'Fault Detection' state if the RF permit shuts OFF and this is true for all of the states in the program. This state also monitors the vacuum limit, if it is within the limit then the sequencer jumps to the 'Hold' state to hold on the current RF power, but it jumps to the 'Vacuum Upper Limit' state if the vacuum crosses the upper limit. When the vacuum reaches below the lower limit then the state checks the variable 'Auto Cycle' and this cycling, which is a part of the RF conditioning process will be discussed in the next chapter. If the 'Auto Cycle' is ON and RF power is greater than or equal to upper limit then the state will hold on the current RF power until the ‘Soak Time’ has been elapsed and jumps to the ‘Decrease’ state but if the ‘Auto Cycle’ is OFF for the same RF power then it simply jumps to the ‘Hold’ state for holding on the current RF power. The sequencer is being looped around the ‘Increase’ state when the RF power is lower than the upper limit for the both ON and OFF condition of the ‘Auto Cycle’. The flow chart of the ‘Increase’ state has been shown in the Figure 4.4.

4.2.3 Decrease State

‘Decrease’ state decrease the RF Power by ‘RF Increment’ step and jumps to the ‘Fault Detection’ during the RF permit OFF situation. The program is being looped around the ‘Decrease’ state if the RF power is greater than the lower limit; otherwise it jumps to the ‘Increase’ state. Figure 4.5 shows the flow diagram of this state.

4.2.4 Hold State

‘Hold’ state is mainly used for holding on the current RF power input to the klystron amplifier from the signal generator. When the vacuum is within the limit and RF amplitude just crossed the upper limit then the sequencer is being looped around this ‘Hold’ state. But if the RF amplitude lowers than the upper limit then it jumps to the ‘Increase’ state to increase the RF power. Moreover, it jumps to the ‘Vacuum Upper Limit’ state if the vacuum crosses the predefined upper limit. If the ‘Auto Cycle’ and ‘RF Permit’ is ON then the state changes to the ‘Decrease’ state to decrease the RF Power. The conditions for the ‘Hold’ state are shown in the Figure 4.6.

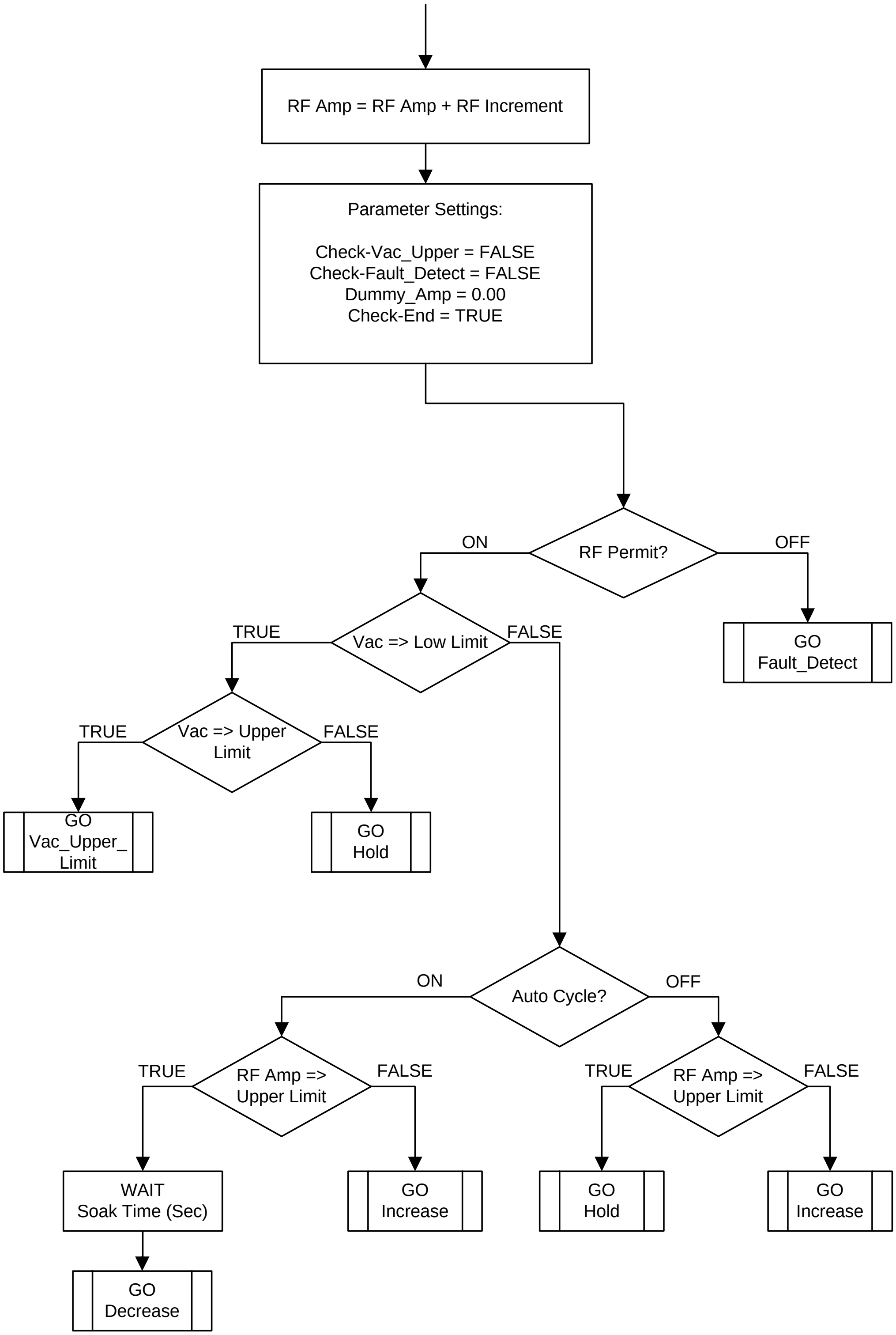


Figure 4.4: Increase state.

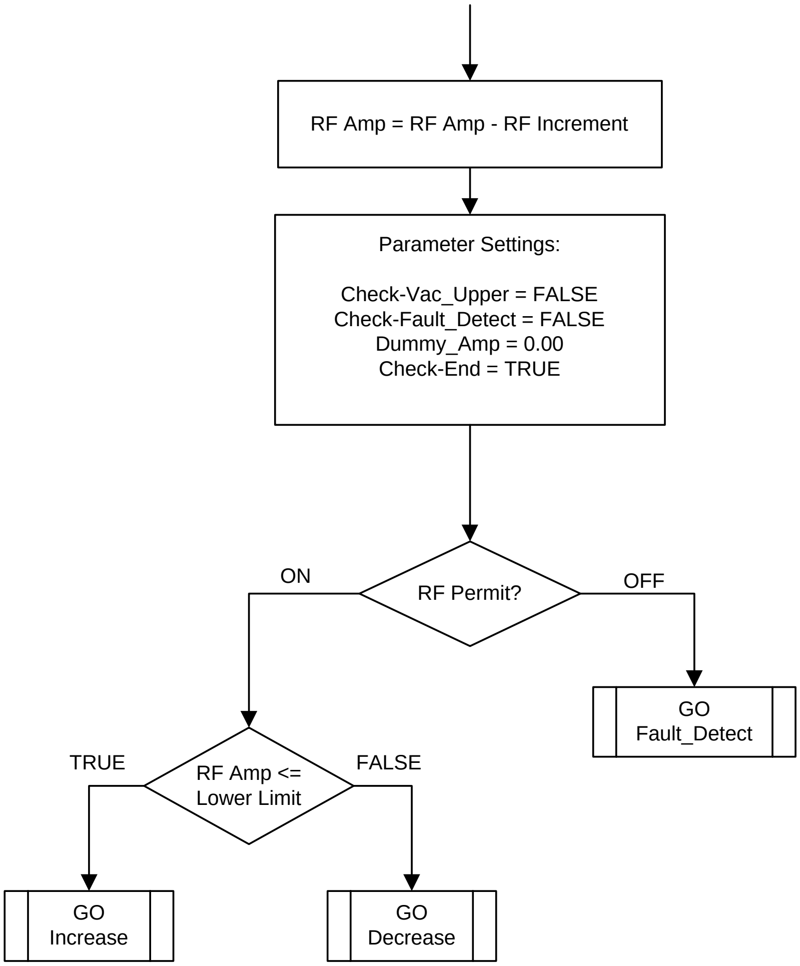


Figure 4.5: Decrease state.

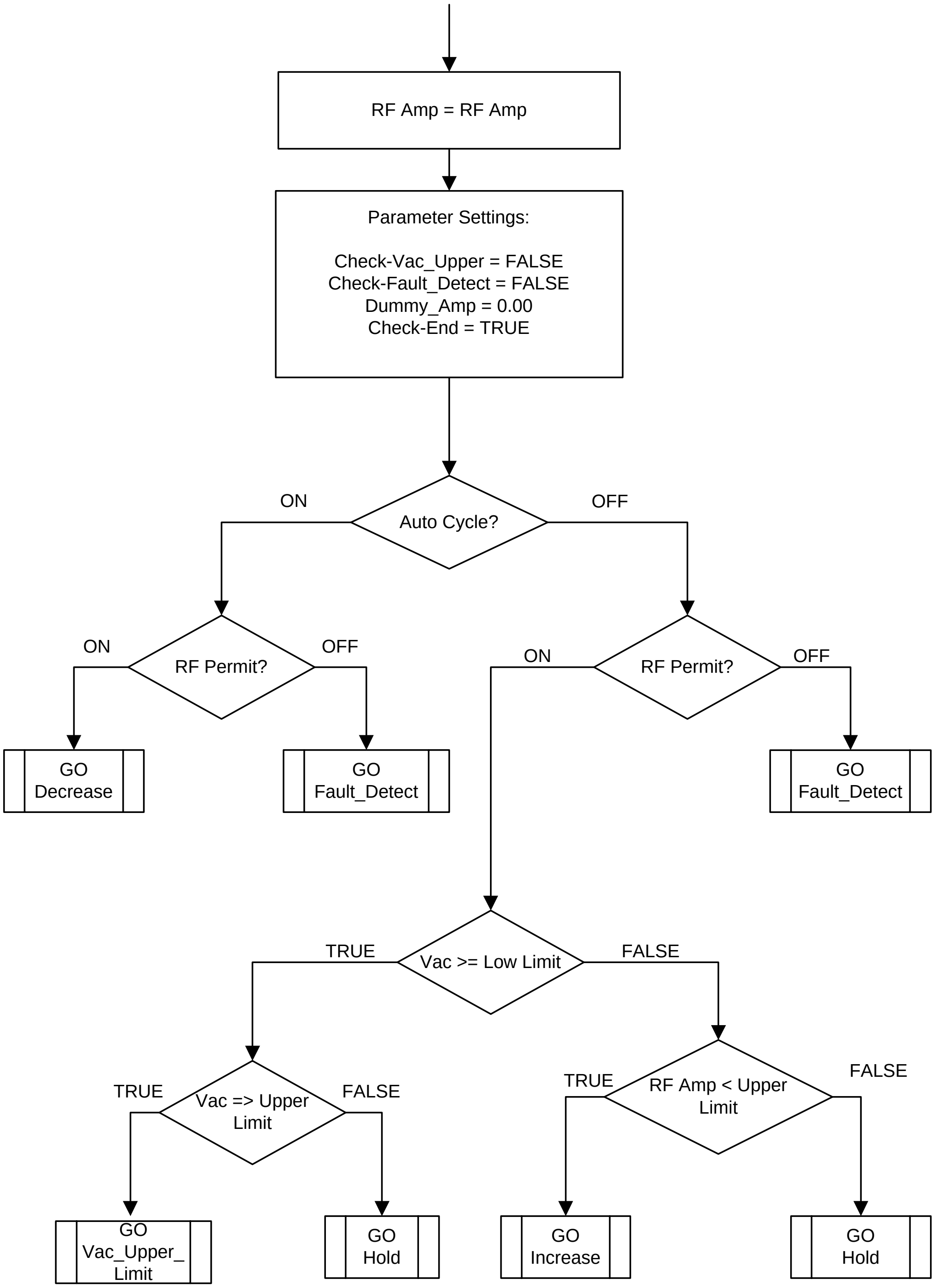


Figure 4.6: Hold state.

4.2.5 Vacuum Upper Limit State

During the RF conditioning process if the vacuum crosses the predefined upper limit then the sequence program jumps to the ‘Vacuum Upper Limit’ state to decrease the RF power. The main difference between this state and the ‘Decrease’ state is – here the decreasing step defined by the variable ‘RF BO Increment’ is much bigger than the step in ‘Decrease’ state. Because if the vacuum crosses the upper limit then the RF power should be backed off by a significant amount and it should be looped around this state until the vacuum reached below the upper limit. When the vacuum is in safe condition then the sequence program goes to the ‘Increase’ state for increasing the power. Figure 4.7 shows the flow diagram of the ‘Vacuum Upper Limit’ state.

4.2.6 Fault Detection State

In any kind of unwanted situation the RF power should be shut OFF and this is control by the variable RF permit. During the process if this permit is OFF then the program immediately jumps to the ‘Fault Detection’ state and shuts down the RF output from the signal generator, decrease the RF power to –40 dB and looping around this state until the fault clears. When the RF permit is ON then the sequencer moves to the ‘Ramp After Fault’ state. The flow diagram of this state has been shown in the Figure 4.8.

4.2.7 Ramp after Fault Detection State

Figure 4.9 shows the detail flow diagram of the ‘Ramp After Fault’ state. After any kind of fault it is desirable to increase the RF power at least by the amount of 1 dB from a very low power such as –40dB to avoid the occurrence of further fault. In ‘Ramp after Fault’

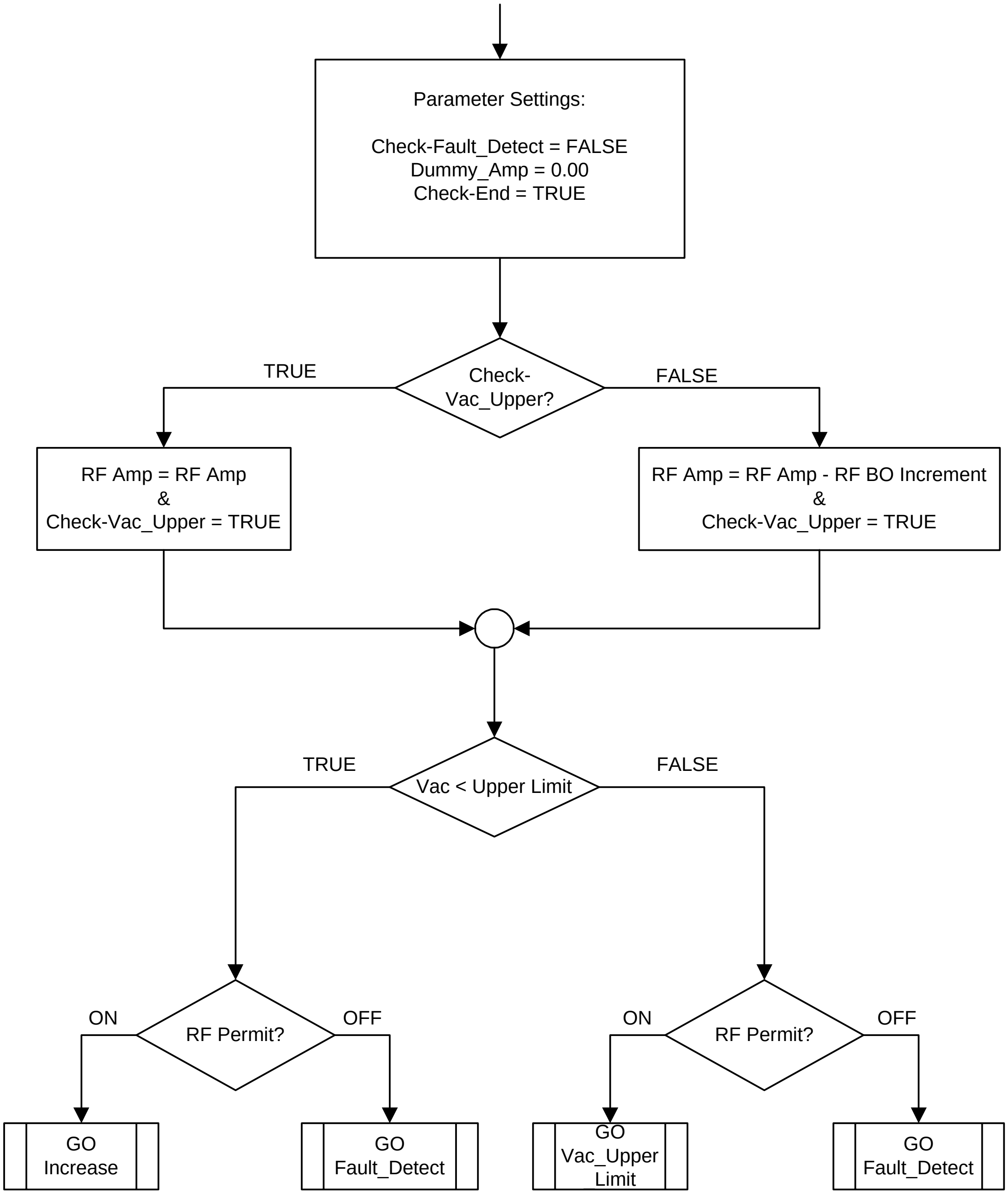


Figure 4.7: Vacuum upper limit state.

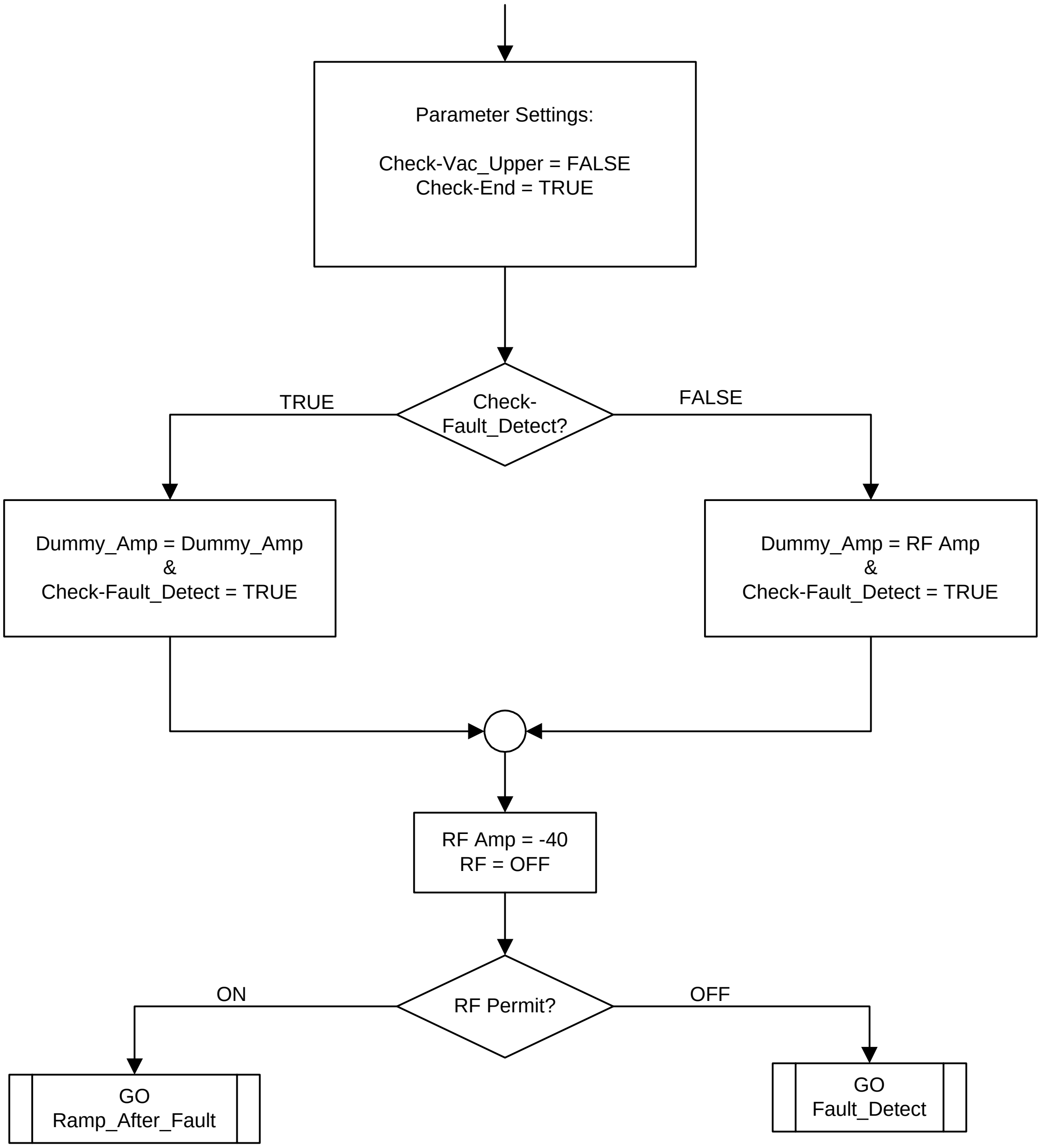


Figure 4.8: Fault detection state.

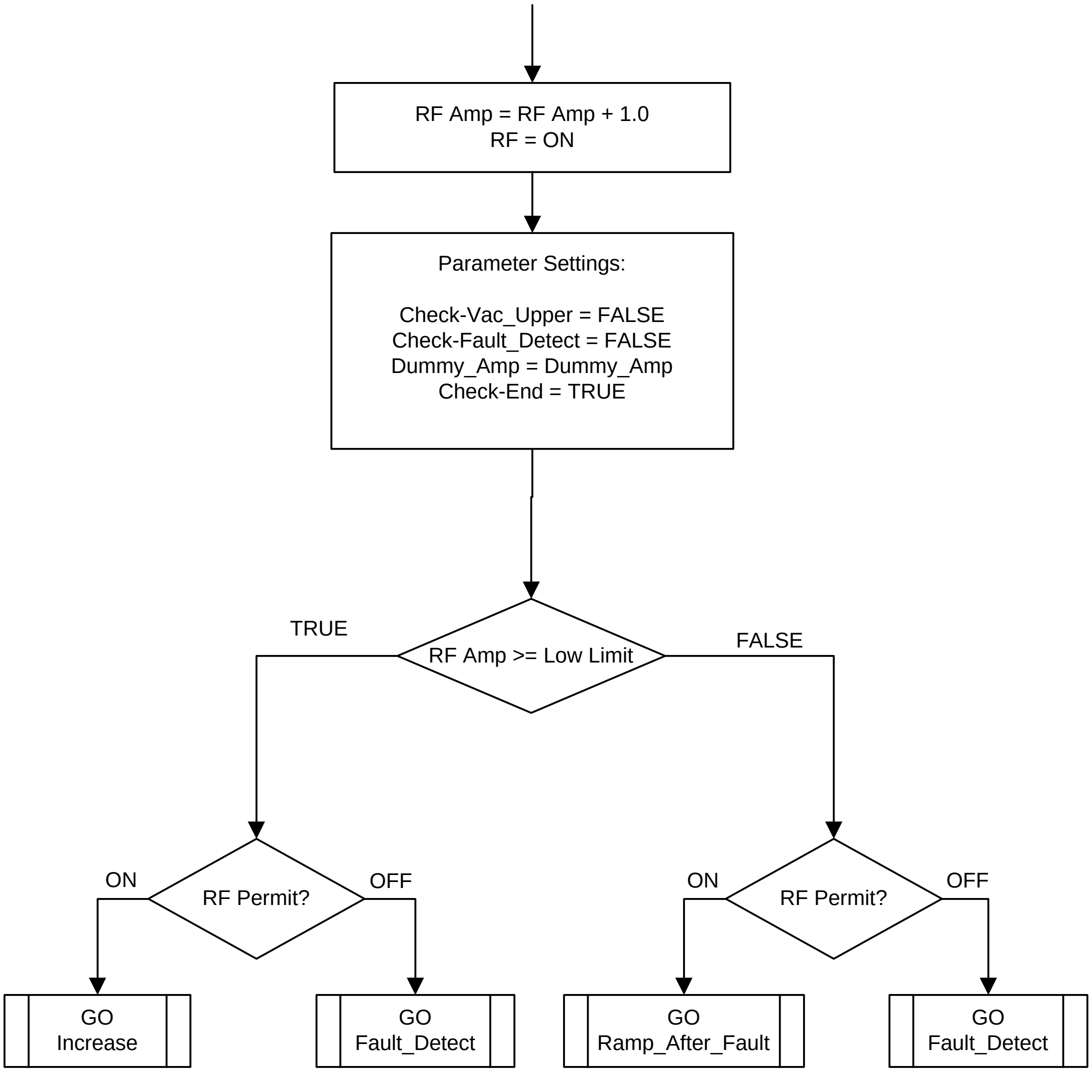


Figure 4.9: Ramp after fault state.

state the output of the RF power is turned ON from the signal generator and it is being looped around this state and increased the power by 1 dB until the Power crossed the lower limit. However when it crosses the lower limit the states switches to ‘Increase’ state.

4.2.8 End State

In the Figure 4.10 the actions of the ‘End’ state has been shown. When the RF conditioning process has been finished, then this state turned OFF the RF power output from the signal generator, sets the power to –60 dB and jumps to the ‘Initialize’ state to start another conditioning process. Moreover, conditioning process can be stop any time by the user and when the user selects the stop button from the main control system then process jumps to this state immediately to shut off the RF conditioning.

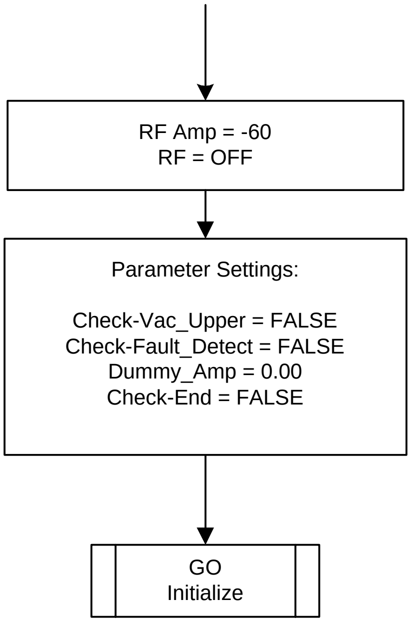


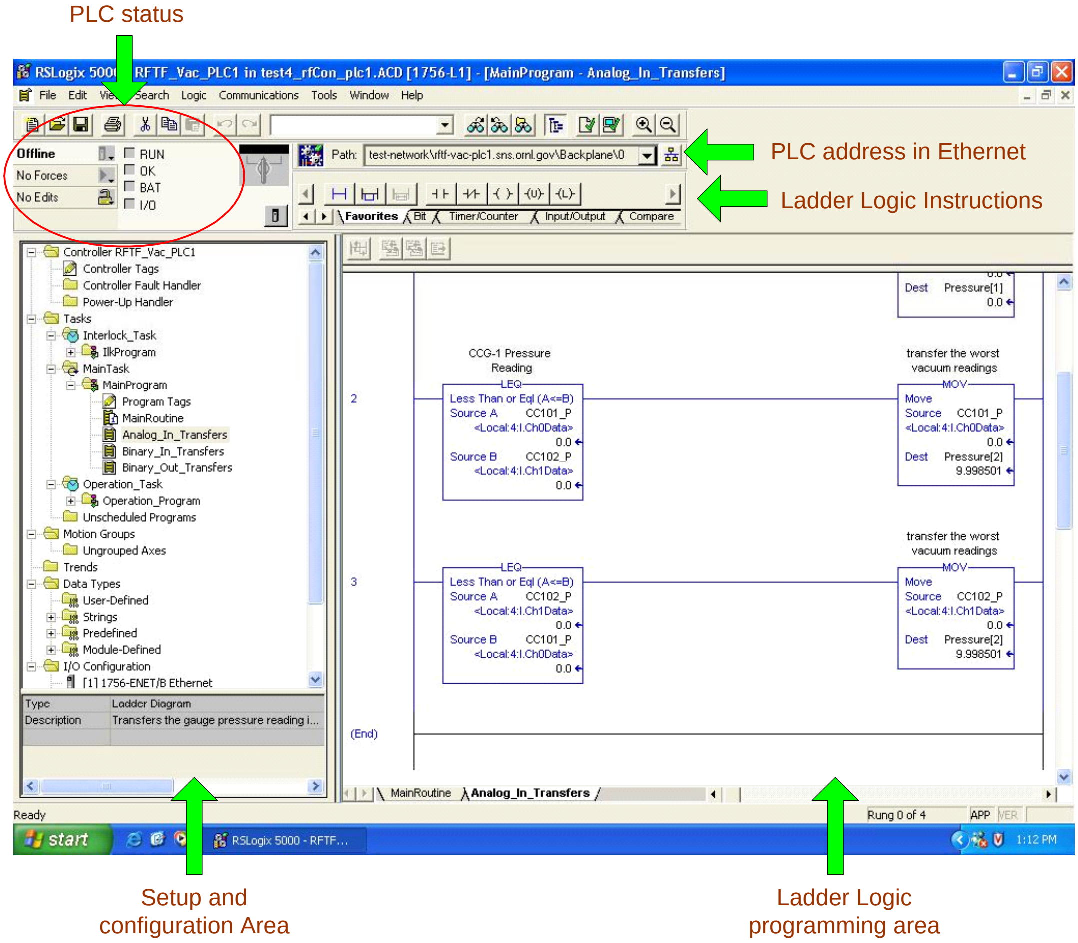
Figure 4.10: End state.

4.3 PLC Programming

In the previous chapter the wiring and the description of the physical structures and various modules of the PLC has been described. However, to control and manage these modules the PLC should be properly programmed. RSLogix 5000 is supplied software to write the ladder logic program for the PLC [34]. It offers reliable communications, easy-to-use, powerful functionality, and superior diagnostics. This software helps to connect with the PLC through the Ethernet or serial connection, helps to configure it; it is also a useful tool to download the ladder logic program and to debug the program in the real time.

The screen shot of the RSLogix 5000 software has been shown in the Figure 4.11. This software has mainly four areas, which has been also shown in that figure. The upper left corner mainly shows the PLC status and mode information, all the ladder logic instructions and the addresses of the PLCs are shown in the upper right corner. While the ladder logic programming and configuration and setup areas are located in the lower section of the RSLogix 5000 software.

The modular type PLC programming structures has been followed in RSLogix 5000 so that the debugging and future upgrading can be done easily and the same software modules can be used in another program. Every program has several ‘task’s and each ‘task’ contain one or more programs and these programs have one or more routines, which are written by using ladder logic instructions. So before writing any PLC control



Path: test-network\rftf-vac-plc1.sns.ornl.gov\Backplane\0

Type: Ladder Diagram
Description: Transfers the gauge pressure reading i...

Dest Pressure[1]
0.0

2
CCG-1 Pressure Reading
LEQ
Less Than or Eql (A<=B)
Source A CC101_P
<Local:4:I.Ch0Data>
0.0
Source B CC102_P
<Local:4:I.Ch1Data>
0.0

transfer the worst vacuum readings
MOV
Move
Source CC101_P
<Local:4:I.Ch0Data>
0.0
Dest Pressure[2]
9.998501

3
LEQ
Less Than or Eql (A<=B)
Source A CC102_P
<Local:4:I.Ch1Data>
0.0
Source B CC101_P
<Local:4:I.Ch0Data>
0.0

transfer the worst vacuum readings
MOV
Move
Source CC102_P
<Local:4:I.Ch1Data>
0.0
Dest Pressure[2]
9.998501

(End)

Figure 4.11: Screen shot of the RSLogix 5000 software for the PLC programming.

system the user should define and construct the flow diagram of the desired PLC operations. In RF conditioning process the PLC always monitors the set point relay status of the VGCs through the digital input module and controls the 24-volt OK signal to the HPM through the digital output module based on the status of these relays. Again, the PLC stores the analog pressure reading from the VGCs in some internal registers so that the 'Vacuum IOC' can access these readings. In the Figure 4.12 the flow diagram of the PLC ladder logic program for the RF conditioning process has been shown.

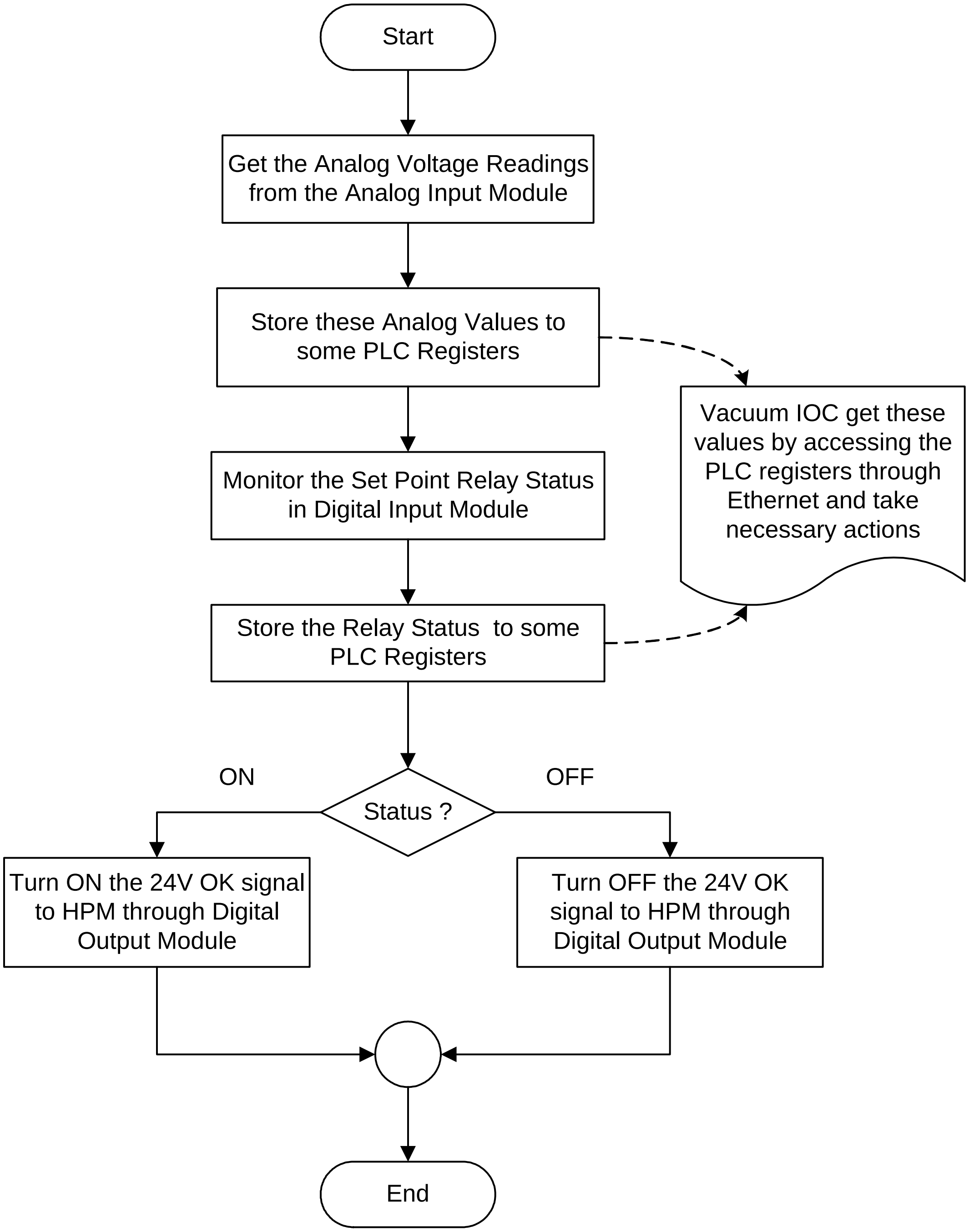


Figure 4.12: Flow chart of the PLC program.

Chapter V

Operation, Results and Analysis

5.1 Conditioning Setup

The developed RF conditioning system can be used for the high power RF processing of any type of RF windows, couplers or cavities. To test the validity and performance of this conditioning system, two Fundamental Power Coupler (FPC)s, which are being used to supply RF power to the SNS superconducting cavities, have been chosen for the high power RF conditioning. As already mentioned in Chapter II, this coupler has a planar annular disk-type of coaxial window, which has been made of 95% alumina ceramic. Furthermore, this FPC must be able to transfer up to 550 kW peak power in 1.3 ms pulses at a repetition rate of 60 pulses per second (pps) during the operation of SNS accelerator. So, it is important to condition these FPCs before placing to the accelerator.

For the conditioning process usually two couplers have been setup back-to-back so that the RF power enters the vacuum waveguide region through one coupler and then exits through the second coupler to a room temperature and matched load. Some self-explanatory pictures from the real time RF conditioning setup at SNS RF Test Facility (RF-TF) has been given in Figures 5.1 through 5.6.

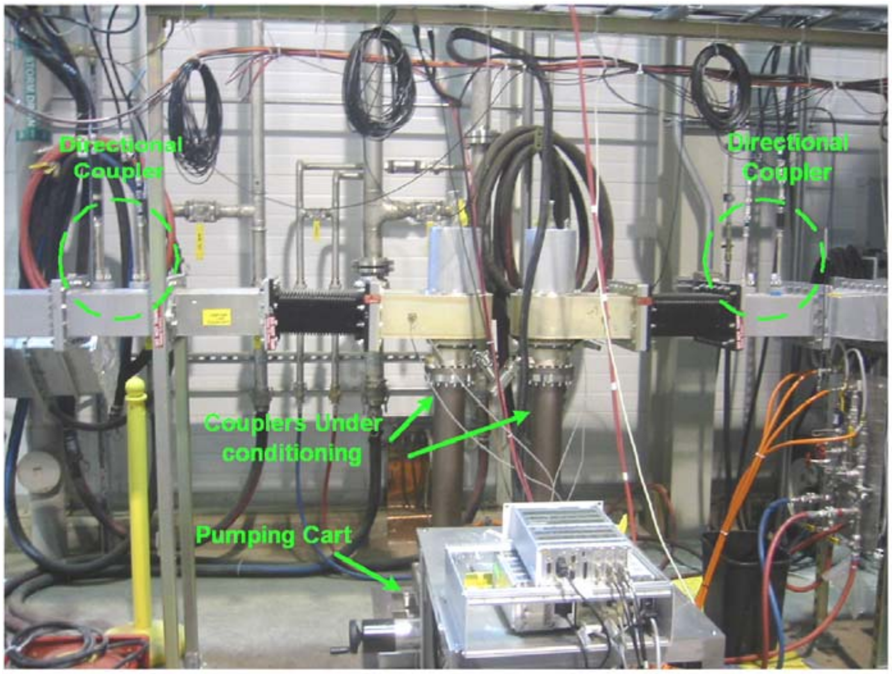


Figure 5.1: Couplers, vacuum pumping cart and the directional couplers.

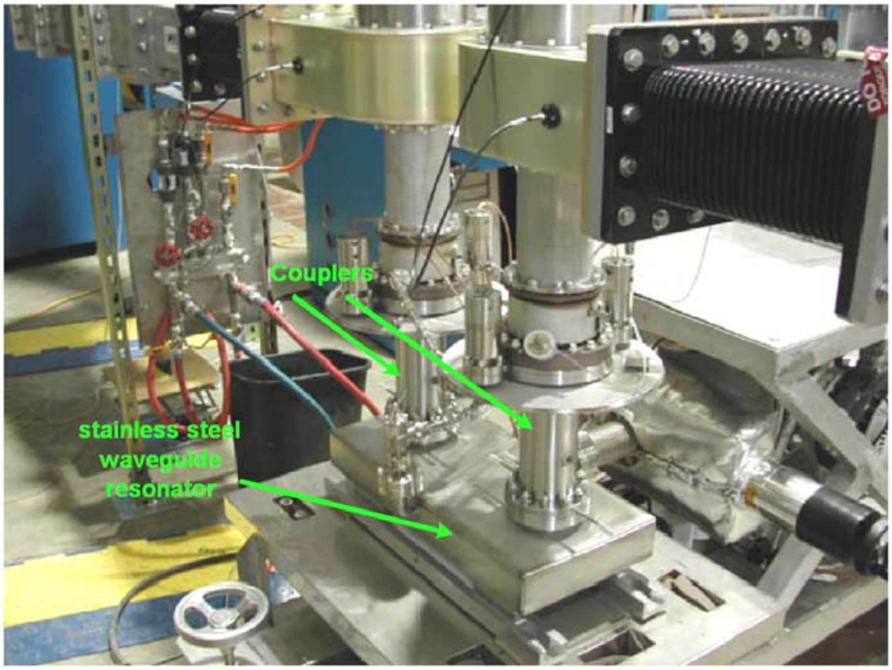


Figure 5.2: Two couplers joined through the waveguide resonator at the bottom.

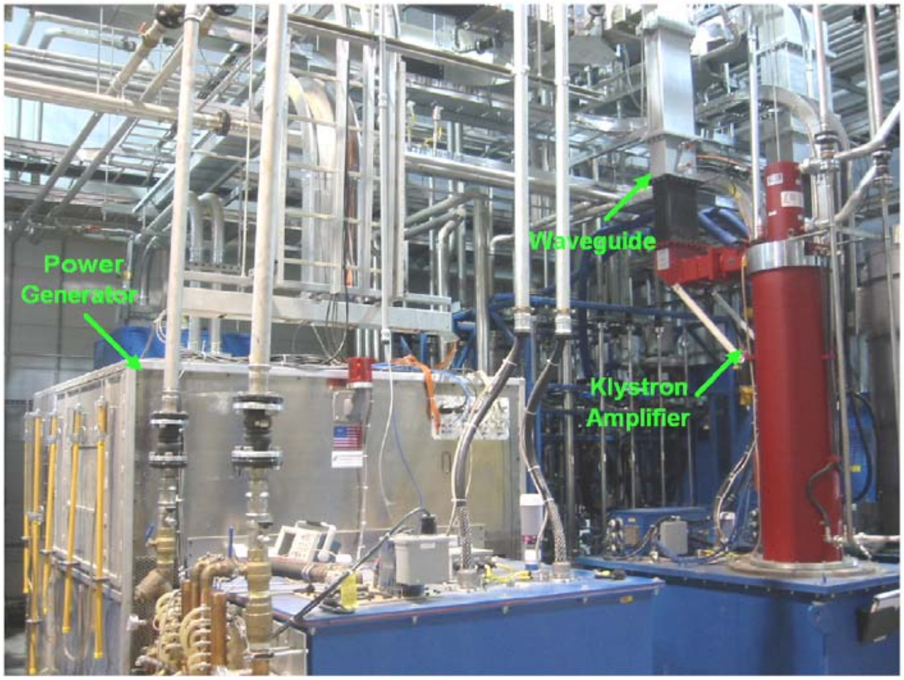


Figure 5.3: Klystron amplifier, power generator and the waveguide.

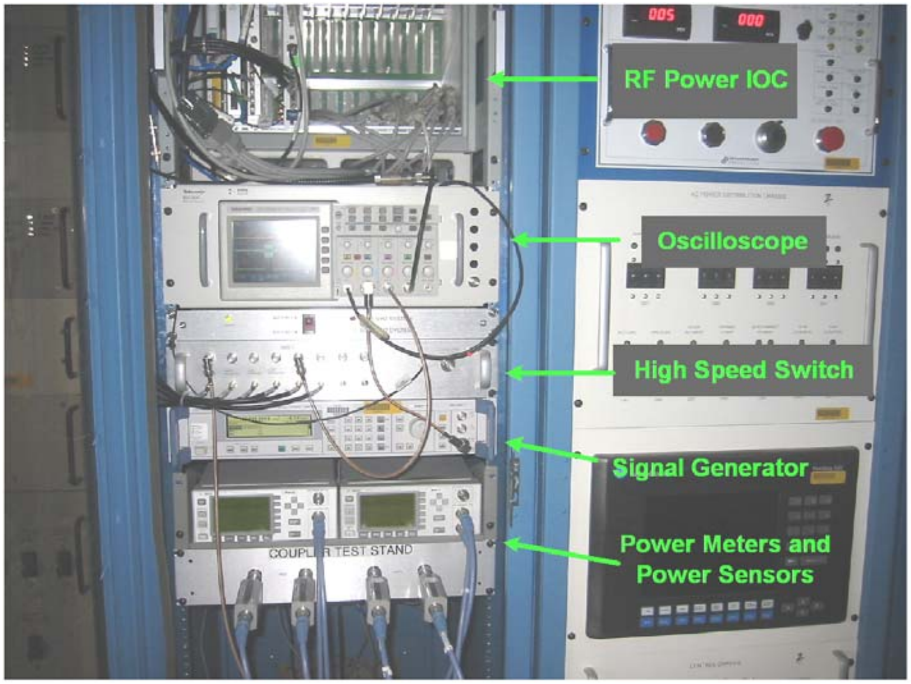


Figure 5.4: RF power IOC and other instruments.

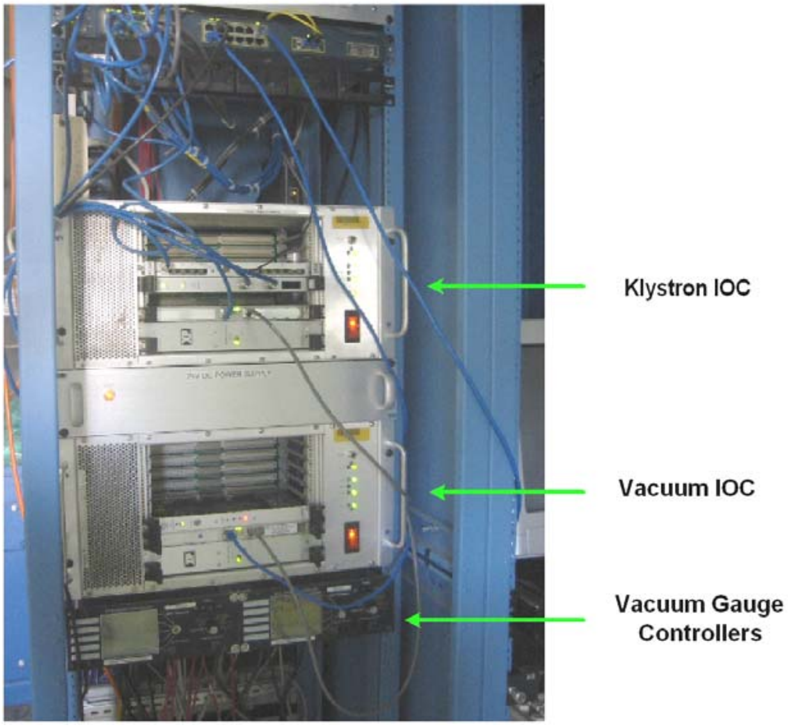


Figure 5.5: Klystron IOC, vacuum IOC and vacuum gauge controllers.

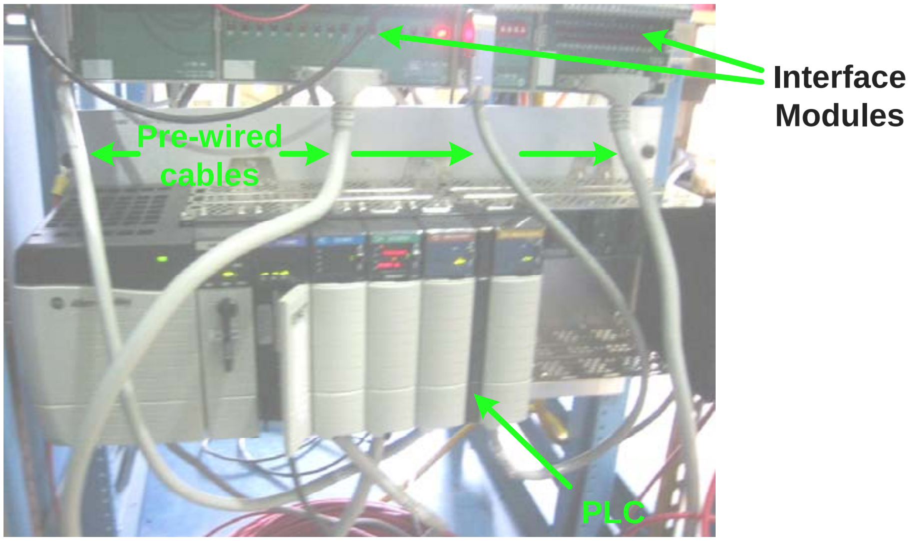


Figure 5.6: PLC, pre-wired cables and interface modules.

A 2.5 MW 805 MHz klystron has been used to transfer the RF power to a water cooled high power load through the FPCs and WR975 waveguide. To control the transmitted RF power levels three sets of directional coupler has been used. Among them, two have been placed between the klystron and the pumping cart and one has been placed between the test cart and the terminating load. Power meters' sensors are connected to the two directional couplers at the input and output section of the FPCs to measure the forward and reflected power. Some attenuators are used in the directional couplers to protect the power sensors from the damage due to the high RF power. However, power meters' channels have been calibrated to compensate this offset power and to display the real time power measurements through the couplers.

High speed vacuum pumping is necessary for the efficient RF conditioning process. A pumping cart designed and developed by the Thomas Jefferson National Accelerator Facility (TJNAF) was used for testing the proposed conditioning system [35]. This mobile aluminum cart houses the vacuum system with a high speed pump, the connecting waveguide for the two FPC's, a de-ionized water-compatible cooling manifold for the inner conductor extensions and all other necessary instrumentations.

Before starting the automated conditioning process, the two FPCs should be installed properly in the pumping cart, the CCG sensors for measuring the vacuum should be connected with the cables, the arc detector sensors should be placed in the proper position to detect arcs in the RF windows during the process and all other necessary connections such as water pipes, grounding cables should be checked.

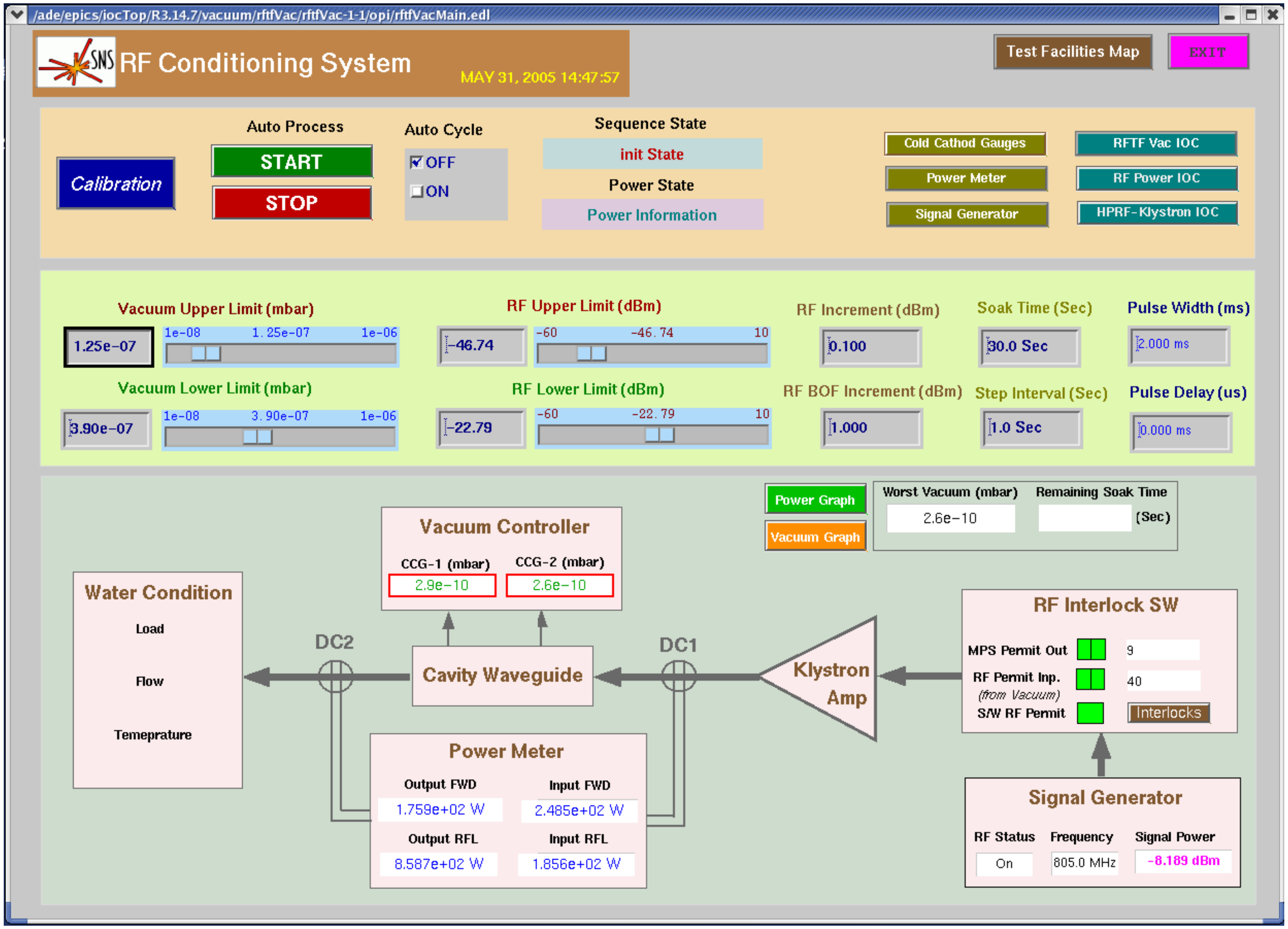
5.2 Description of the Main Operator Interface (OPI)

The main Operator Interface (OPI) for the developed RF conditioning system has been designed by using the EDM software of EPICS. It has been designed in such a way that the operator can observe the status of any instrument, set the parameters, control every step of the conditioning process, and archive the data and results very easily. The EDM screen of the designed OPI is shown in the Figure 5.7.

The designed OPI has mainly four sections and all the sections have been separated by different background colors. The topmost section provides the current date, time and two links to go to the main screen of the test facility and to exit from the current screen.

The second section has all the control switches, such as calibration, start, stop, and auto-cycle. It also shows the current processing state and the power from the main sequence program in the 'Sequence State' and the 'Power State' windows respectively. Moreover, some buttons has been placed on the right side of this section to browse all the IOCs' and instruments' information individually.

The third section of the main OPI has been designed for setting up all the necessary parameters for the RF conditioning process. To increase the reliability of the proposed system both the hard-limit and soft-limit for the vacuum and RF power has been



/ade/epics/iocTop/R3.14.7/vacuum/rftfVac/rftfVac-1-1/opi/rftfVacMain.edl

RF Conditioning System MAY 31, 2005 14:47:57

Auto Cycle: ☑ OFF ☐ ON

Sequence State: init State

Power State: Power Information

Vacuum Upper Limit (mbar): 1.25e-07 (1e-08 1.25e-07 1e-06)

Vacuum Lower Limit (mbar): 3.90e-07 (1e-08 3.90e-07 1e-06)

RF Upper Limit (dBm): -46.74 (-60 -46.74 10)

RF Lower Limit (dBm): -22.79 (-60 -22.79 10)

RF Increment (dBm): 0.100

RF BOF Increment (dBm): 1.000

Soak Time (Sec): 30.0 Sec

Step Interval (Sec): 1.0 Sec

Pulse Width (ms): 2.000 ms

Pulse Delay (us): 0.000 ms

Worst Vacuum (mbar): 2.6e-10

Remaining Soak Time (Sec):

Vacuum Controller

CCG-1 (mbar): 2.9e-10

CCG-2 (mbar): 2.6e-10

Power Meter

Output FWD: 1.759e+02 W

Input FWD: 2.485e+02 W

Output RFL: 8.587e+02 W

Input RFL: 1.856e+02 W

RF Interlock SW

MPS Permit Out 🟩🟩 9

RF Permit Inp. *(from Vacuum)* 🟩🟩 40

S/W RF Permit 🟩

Signal Generator

RF Status: On

Frequency: 805.0 MHz

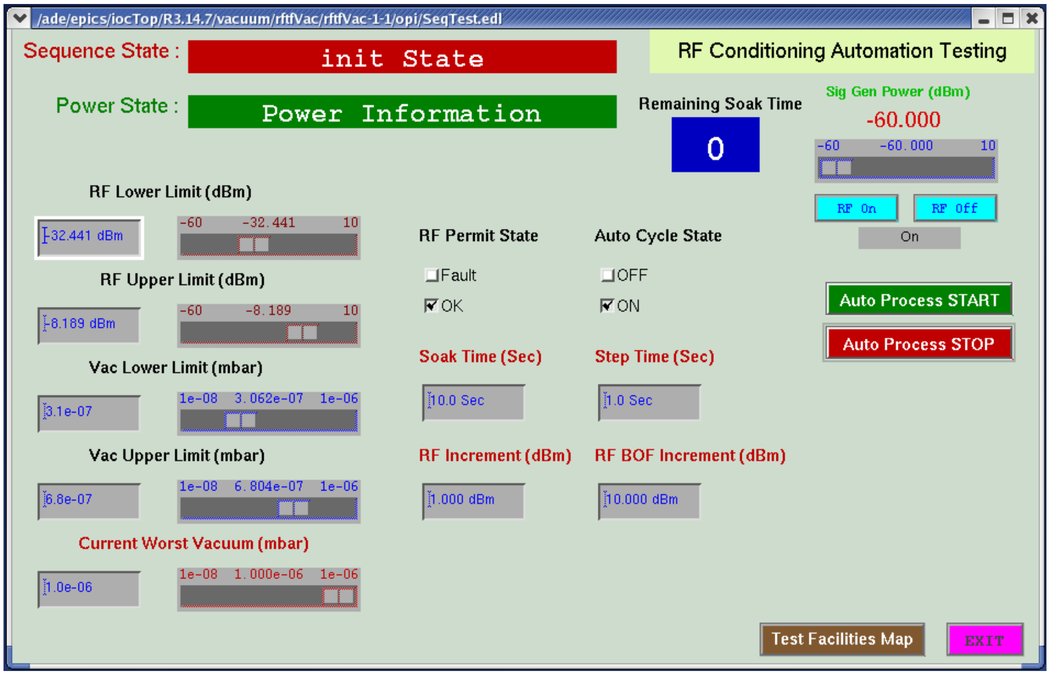
Signal Power: -8.189 dBm

Figure 5.7: Main operator interface (OPI) screen for the RF conditioning system.

provided. This section provides the control for the all soft-limits. Furthermore, the various increment steps and timings can be configured here also.

The last section of the main OPI provides all the measurement data from the vacuum controllers, power meters and the signal generator. The condition of the RF interlock switch and water cooling system can be monitored here also. This section also contains two buttons for plotting the vacuum and RF power graphs during the conditioning process. EPICS StripTool software is being used to generate these graphs. Operator has the flexibility to configure the graphing display and save the data anytime. Moreover, the remaining soak time can be monitored from this section during the auto cycle conditioning.

Sequence program is the main program which is running all the time during the RF processing and controls the sequence based on the real time power and vacuum measurements and other necessary conditions. Therefore, this program should be tested and debugged before the actual RF conditioning process to avoid any kind of trouble in the system. For fulfilling this purpose another OPI has been designed just for testing the sequence program with some dummy parameters. Figure 5.8 shows the OPI screen of that. In this OPI, some real time parameters such as current worst vacuum reading and the RF permit state can be controlled with some dummy values. However, in actual system the sequence program get these values from the HPM and the vacuum controllers. Furthermore, this OPI has all necessary options and parameter settings of the main OPI.


/ade/epics/iocTop/R3.14.7/vacuum/rftfVac/rftfVac-1-1/opi/SeqTest.edl

RF Conditioning Automation Testing

Sequence State : init State

Power State : Power Information

Remaining Soak Time: 0

Sig Gen Power (dBm): -60.000

RF Lower Limit (dBm): -32.441 dBm

RF Upper Limit (dBm): -8.189 dBm

Vac Lower Limit (mbar): 3.1e-07

Vac Upper Limit (mbar): 6.8e-07

Current Worst Vacuum (mbar): 1.0e-06

RF Permit State: ☐ Fault ☑ OK

Auto Cycle State: ☐ OFF ☑ ON

Soak Time (Sec): 10.0 Sec

Step Time (Sec): 1.0 Sec

RF Increment (dBm): 1.000 dBm

RF BOF Increment (dBm): 10.000 dBm

Figure 5.8: OPI screen for testing the sequence program.

5.3 Procedures for the RF Conditioning Process

The procedure developed by the SNS for the RF conditioning of FPCs has been followed throughout the test [36].

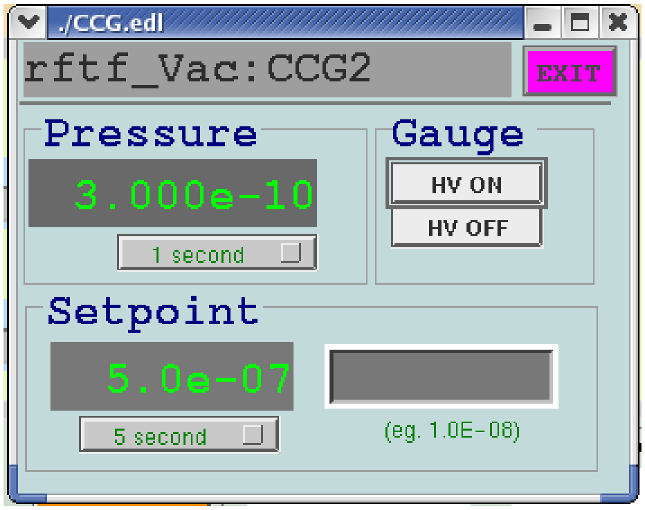
Qualified personnel with proper training are allowed to operate the conditioning process. Before starting the process the FPCs were baked at 200 degree Celsius temperature for 60 hours by using TJNAF's baking cart [35].

The conditioning process consists of two wave modes – traveling wave mode and the standing wave mode. During the traveling wave mode RF power is being transferred from the klystron to load through the couplers to be conditioned. However, in standing wave mode the load is replaced with a variable short, which produces a standing wave between the short and the klystron and this wave is being passed through the couplers thoroughly. The detailed procedures of each mode and the initial setup have been described below.

5.3.1 Before Starting the RF Conditioning

The following steps should be done before starting the conditioning –

- Power meters' sensors should be calibrated and zeroed by following the procedures in the operation manual [28]. Moreover, the offset value of the attenuator, placed in the directional couplers, should be added to the power meter channels for giving the correct power measurements.
- The value of the relay set points for each gauge in the vacuum gauge controllers should be set and checked. Conditioning process will be shut down if the vacuum crosses this maximum limit. The limit 5×10^{-7} mBar has been chosen and it can be setup from the main OPI screen or manually from the instrument. Figure 5.9 shows an OPI screen for the gauge setup in a vacuum controller.
- The signal generator's output should be connected to the interlock switch and proper operating frequency and parameters of the pulse modulation should be set up from the EPICS screen. In Figure 5.10, the OPI screen for the signal generator and power meter has been shown.
- The connection of the fiber optic sensors of the arc detector should be checked. Moreover, they should be enabled from the OPI screen shows in the Figure 5.11.



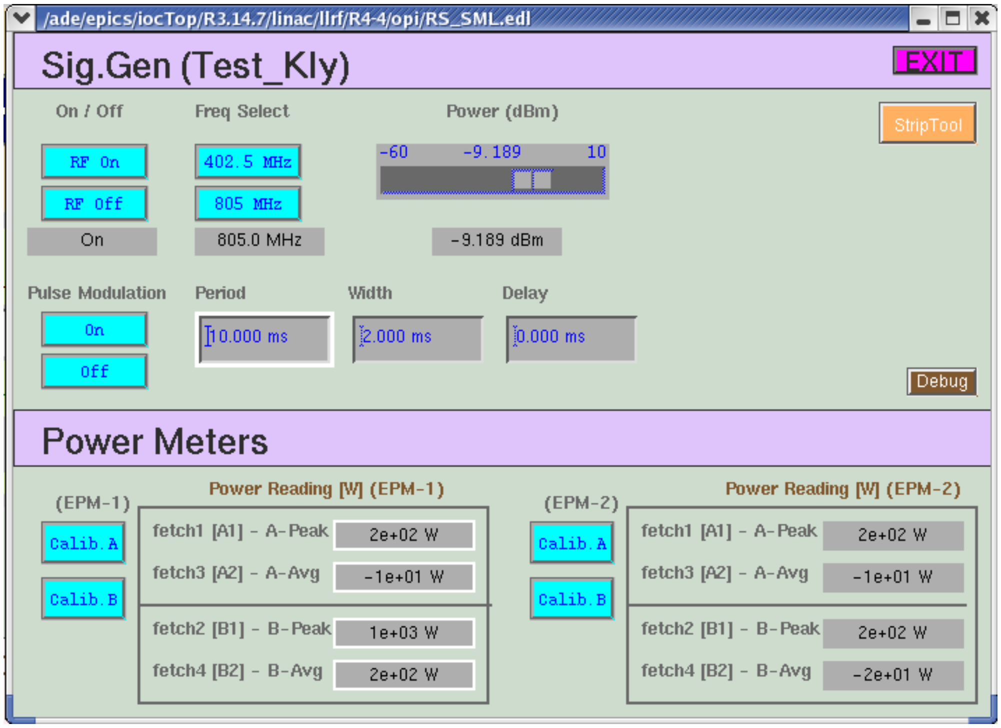
rftf_Vac:CCG2

Pressure
3.000e-10
1 second

Gauge

Setpoint
5.0e-07
5 second
(eg. 1.0E-08)

Figure 5.9: OPI screen for controlling the vacuum gauges in vacuum controllers.



Sig.Gen (Test_Kly)

On / Off: On

Freq Select: 805.0 MHz

Power (dBm): -9.189 dBm

Pulse Modulation

Period: 10.000 ms

Width: 2.000 ms

Delay: 0.000 ms

Power Meters

(EPM-1)

Power Reading [W] (EPM-1)

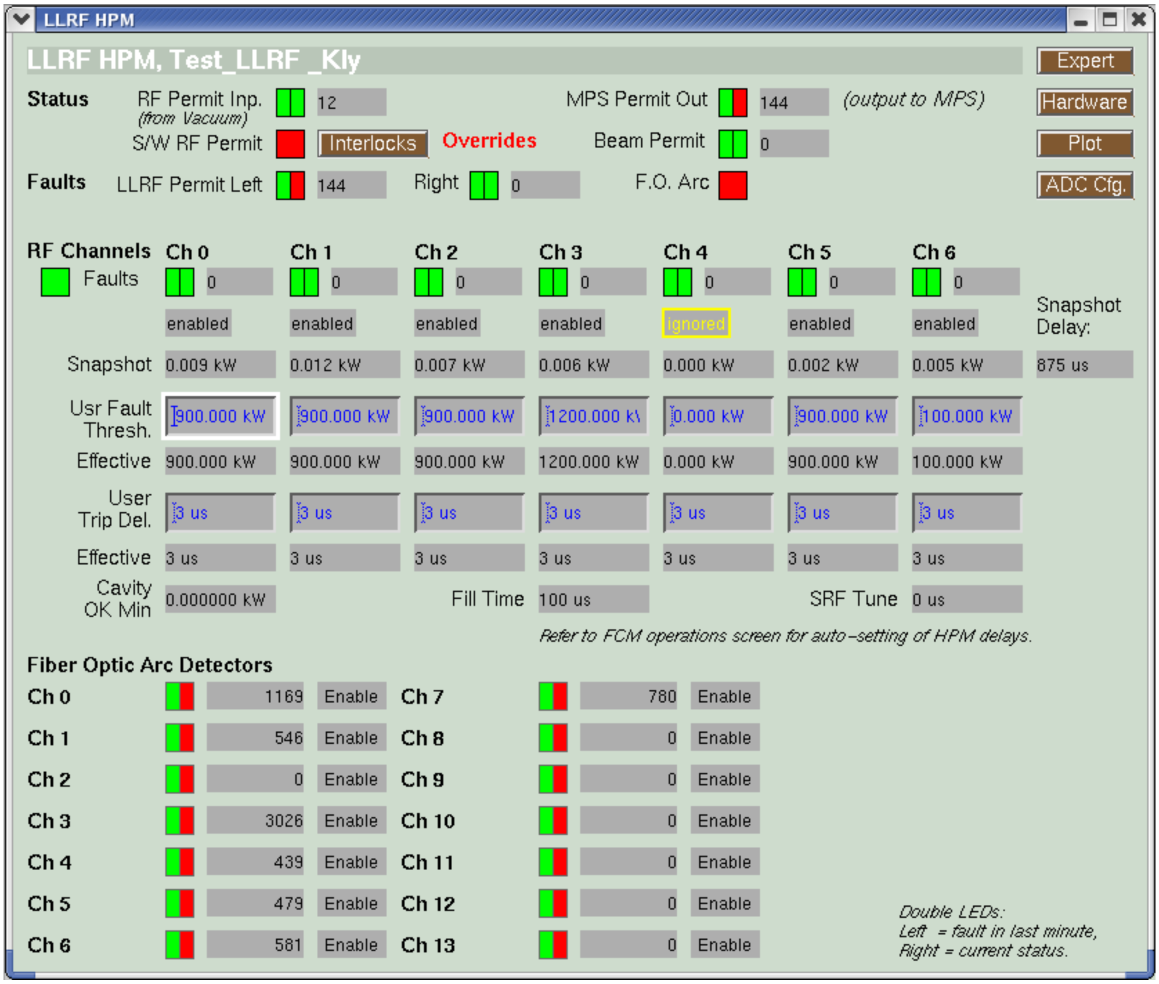
fetch1 [A1] - A-Peak 2e+02 W
fetch3 [A2] - A-Avg -1e+01 W
fetch2 [B1] - B-Peak 1e+03 W
fetch4 [B2] - B-Avg 2e+02 W

(EPM-2)

Power Reading [W] (EPM-2)

fetch1 [A1] - A-Peak 2e+02 W
fetch3 [A2] - A-Avg -1e+01 W
fetch2 [B1] - B-Peak 2e+02 W
fetch4 [B2] - B-Avg -2e+01 W

Figure 5.10: OPI screen for the signal generator and power meters.



LLRF HPM, Test_LLRF _Kly

Status

RF Permit Inp. (from Vacuum)	🟩🟩	12	MPS Permit Out	🟩🟥	144 (output to MPS)
S/W RF Permit	🟥	Interlocks	Beam Permit	🟩🟩	0

Faults

LLRF Permit Left	🟩🟥	144	Right	🟩🟩	0	F.O. Arc	🟥

RF Channels 🟩 Faults

	Ch 0	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	
Faults	🟩🟩 0	🟩🟩 0	🟩🟩 0	🟩🟩 0	🟩🟩 0	🟩🟩 0	🟩🟩 0	
	enabled	enabled	enabled	enabled	ignored	enabled	enabled	Snapshot Delay:
Snapshot	0.009 kW	0.012 kW	0.007 kW	0.006 kW	0.000 kW	0.002 kW	0.005 kW	875 us
Usr Fault Thresh.	900.000 kW	900.000 kW	900.000 kW	1200.000 k\	0.000 kW	900.000 kW	100.000 kW	
Effective	900.000 kW	900.000 kW	900.000 kW	1200.000 kW	0.000 kW	900.000 kW	100.000 kW	
User Trip Del.	3 us	3 us	3 us	3 us	3 us	3 us	3 us	
Effective	3 us	3 us	3 us	3 us	3 us	3 us	3 us	

Cavity OK Min 0.000000 kW

Fill Time 100 us

SRF Tune 0 us

Refer to FCM operations screen for auto-setting of HPM delays.

Fiber Optic Arc Detectors

Ch 0	🟩🟥	1169	Enable	**Ch 7**	🟩🟥	780	Enable
Ch 1	🟩🟥	546	Enable	**Ch 8**	🟩🟥	0	Enable
Ch 2	🟩🟥	0	Enable	**Ch 9**	🟩🟥	0	Enable
Ch 3	🟩🟥	3026	Enable	**Ch 10**	🟩🟥	0	Enable
Ch 4	🟩🟥	439	Enable	**Ch 11**	🟩🟥	0	Enable
Ch 5	🟩🟥	479	Enable	**Ch 12**	🟩🟥	0	Enable
Ch 6	🟩🟥	581	Enable	**Ch 13**	🟩🟥	0	Enable

Double LEDs:
Left = fault in last minute,
Right = current status.

Figure 5.11: OPI screen for setting up and monitoring the instruments connected with the HPM in RF power IOC.

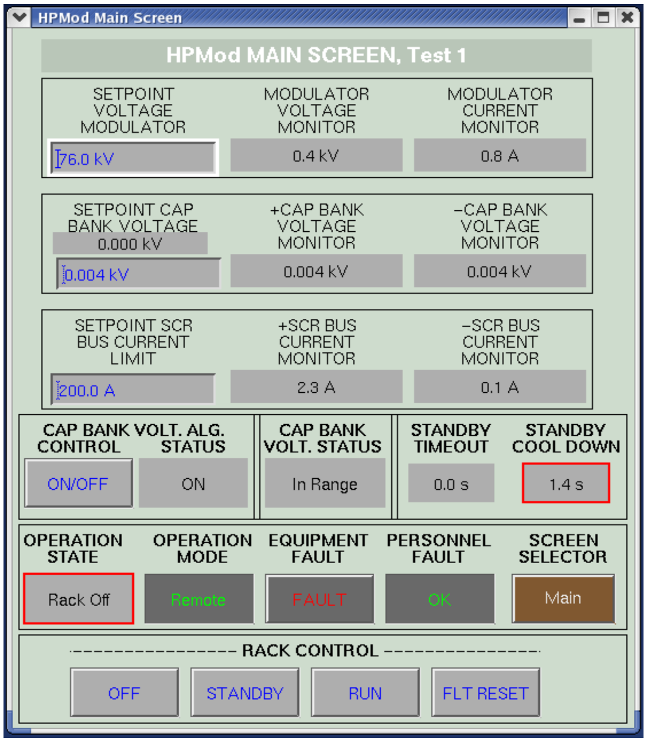
5.3.2 RF Conditioning with Traveling Wave

The conditioning process with the traveling wave have been summarized below-

- Since the vacuum inside the coupler is very bad initially so the conditioning process should be start from a very low RF power and should be increased very slowly. Table 5.1 shows the various limits and parameters, which have been chosen to start the process.
- Power and vacuum graphs should be opened by pressing the ‘Power Graph’ and ‘Vacuum Graph’ buttons respectively.
- After setting up all the parameters the conditioning process is started by pressing the ‘START’ button in the main OPI screen.
- Initially processing has been started with 0.5 msec pulse width and 10 Hz pulse rate of the signal generator to reach 300 kW.
- Run the converter modulator with low voltage and for higher power increase the set-point voltage gradually. Figure 5.12 shows the OPI screen to control he High Power Modulator (HPMod).
- Cycle the RF power between 0 to 650 kW for more than 8 hours (12 hours is desirable) by selecting the ‘Auto Cycle’ ON and setting up the ‘Soak Time’ in the main OPI.
- The next step is Cycle Constant Cycle (CCC) testing. Cycle RF power between 0 to 650 kW for 1 hour, constant power run at 650 kW for 3 hours and again cycle RF power between 0 to 650 kW for 1 hour.

Table 5.1: Example of the conditioning parameters.

Parameters	Value
Vacuum upper limit	$3.0\text{x}10^{-7}$ mBar
Vacuum lower limit	$2.5\text{x}10^{-7}$ mBar
RF upper limit	2 dBm
RF lower limit	-20 dBm
RF increment	0.1 dBm
RF back off increment	3 dBm
RF fault increment	1 dBm
Soak time	30 sec
Step interval	1.0 sec
Pulse width	0.5 msec
Pulse period	100 msec



SETPOINT VOLTAGE MODULATOR: 76.0 kV
MODULATOR VOLTAGE MONITOR: 0.4 kV
MODULATOR CURRENT MONITOR: 0.8 A
SETPOINT CAP BANK VOLTAGE: 0.000 kV
0.004 kV
+CAP BANK VOLTAGE MONITOR: 0.004 kV
–CAP BANK VOLTAGE MONITOR: 0.004 kV
SETPOINT SCR BUS CURRENT LIMIT: 200.0 A
+SCR BUS CURRENT MONITOR: 2.3 A
–SCR BUS CURRENT MONITOR: 0.1 A
CAP BANK VOLT. ALG. STATUS: ON
CAP BANK VOLT. STATUS: In Range
STANDBY TIMEOUT: 0.0 s
STANDBY COOL DOWN: 1.4 s
OPERATION STATE: Rack Off
OPERATION MODE: Remote
EQUIPMENT FAULT: FAULT
PERSONNEL FAULT: OK
SCREEN SELECTOR: Main

Figure 5.12: OPI screen for the high power modulator.

- After CCC testing conditioning should be done with DC bias (upto 2.5 kV) at the maximum power for 3 hours total. The steps are given below-
    a. Cycle RF power for 30 minutes with no (0 V) DC bias.
    b. Constant power for 30 minutes with no (0 V) DC bias.
    c. Cycle RF power for 30 minutes with negative (-2.5 kV) DC bias.
    d. Constant power for 30 minutes with negative (-2.5 kV) DC bias.
    e. Cycle RF power for 30 minutes with positive (+2.5 kV) DC bias.
    f. Constant power for 30 minutes with positive (+2.5 kV) DC bias.
- Finally constant power should be supplied at the maximum power for more than 8 hours and the conditioning with standing wave should be started after that.

5.3.3 RF Conditioning with Standing Wave

- Waveguide has to be terminated with a variable short.
- Constant power should be given at different power levels, such as 100 kW steps to reach 600 kW maximum, for 3 to 4 hours in total.
- Variable short should be moved for 7 to 8 times with 30 minutes at each power level.

5.3.4 After the Conditioning

- Pressing the switch labeled ‘STOP’ in the main OPI screen finishes conditioning process.
- After the conditioning the High Voltage Converter Modulator (HVCM) and transmitters should be turned off.

- The data and graph for the power and vacuum should be saved for the future analysis.
- All the windows, programs, computers and instruments should be turned off.

In Figure 5.13, the RF conditioning steps described above are summarized graphically [36].

5.4 Results and Analysis

Several experiments were performed at RF Test Facility (RF-TF) of SNS to determine the validity and performance of the proposed RF conditioning system. In this section we will describe and present the results obtained so far. Usually, the following qualities are expected from an automated RF conditioning system-

- Smooth starting with gradual increase of the RF power.
- The control system will increase, decrease, hold or back off the RF power depending on the vacuum.
- RF power will be shut down during any kind of fault and the system will increase the power automatically after the fault.
- Auto cycling and constant power supplying should work efficiently.

So, we will focus on these issues to present and analysis the results [37].

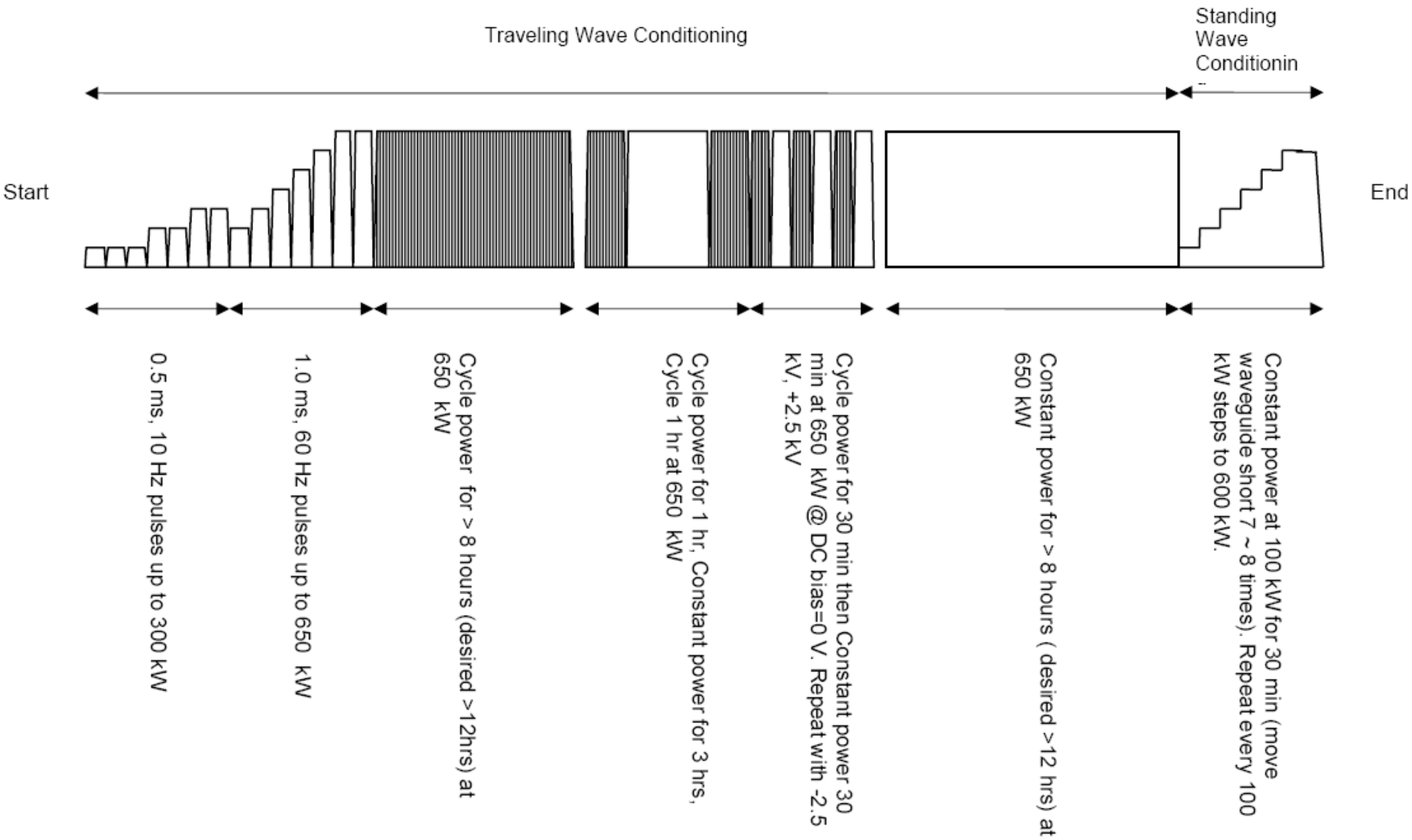


Figure 5.13: The summary of the RF conditioning procedures [36].

5.4.2 Results in Traveling Wave Mode

A number of power graphs and corresponding vacuum graphs has been presented here. In the power graphs the input and output forward power has been represented by blue and red colors respectively, while in the vacuum graphs these colors represented the vacuum pressure in the first and second couplers respectively. Figure 5.14 shows the first one-hour conditioning results during the traveling wave mode. It also shows the smooth starting of the conditioning process with the gradual increase of power. In the Figure 5.15, the magnify version of the conditioning process has been shown with a small timing scale in the X-axis. It is clear from this figure that how RF power is backed off and increased again when the vacuum has been crossed the predefined upper limit. Figure 5.16 shows the two hours conditioning results. It is noticeable from this figure that after one hour conditioning the vacuum activities went high and during that time RF power has been hold on by the system. After two and half hour of conditioning during the traveling wave mode the modulator, which supplies the voltage to the klystron amplifier, was tripped off for the lack of required water flow to cool down the system. During this time the conditioning process stopped the RF power and started it again after the fault recovery. Figure 5.17 shows this data. In the figure 5.18, the results of the auto cycle conditioning and the constant power conditioning has been shown. Finally, figure 5.19 shows how the vacuum was changing during the soaking time of the auto cycle conditioning in magnified time scale of the X-axis.

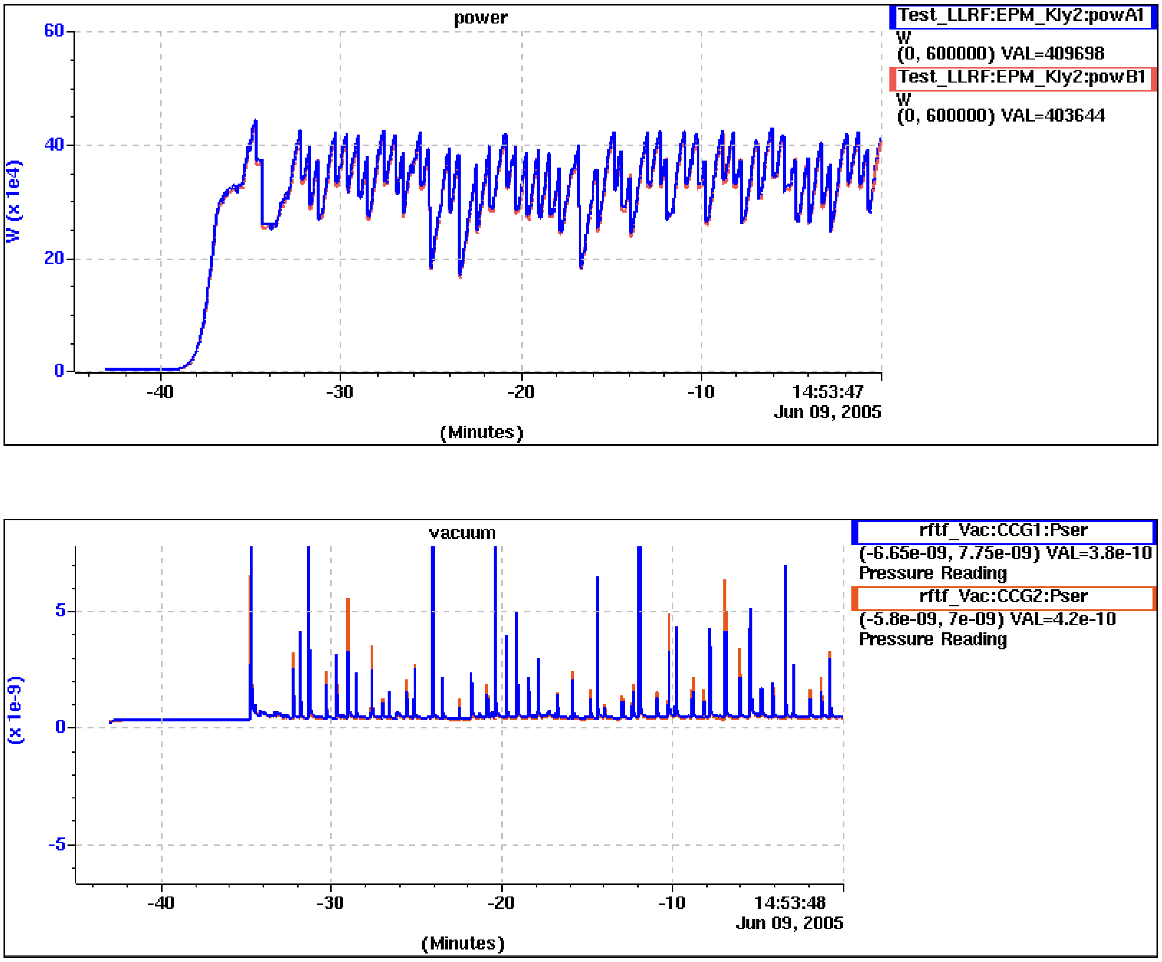


Figure 5.14: First one hour conditioning results in traveling wave mode.

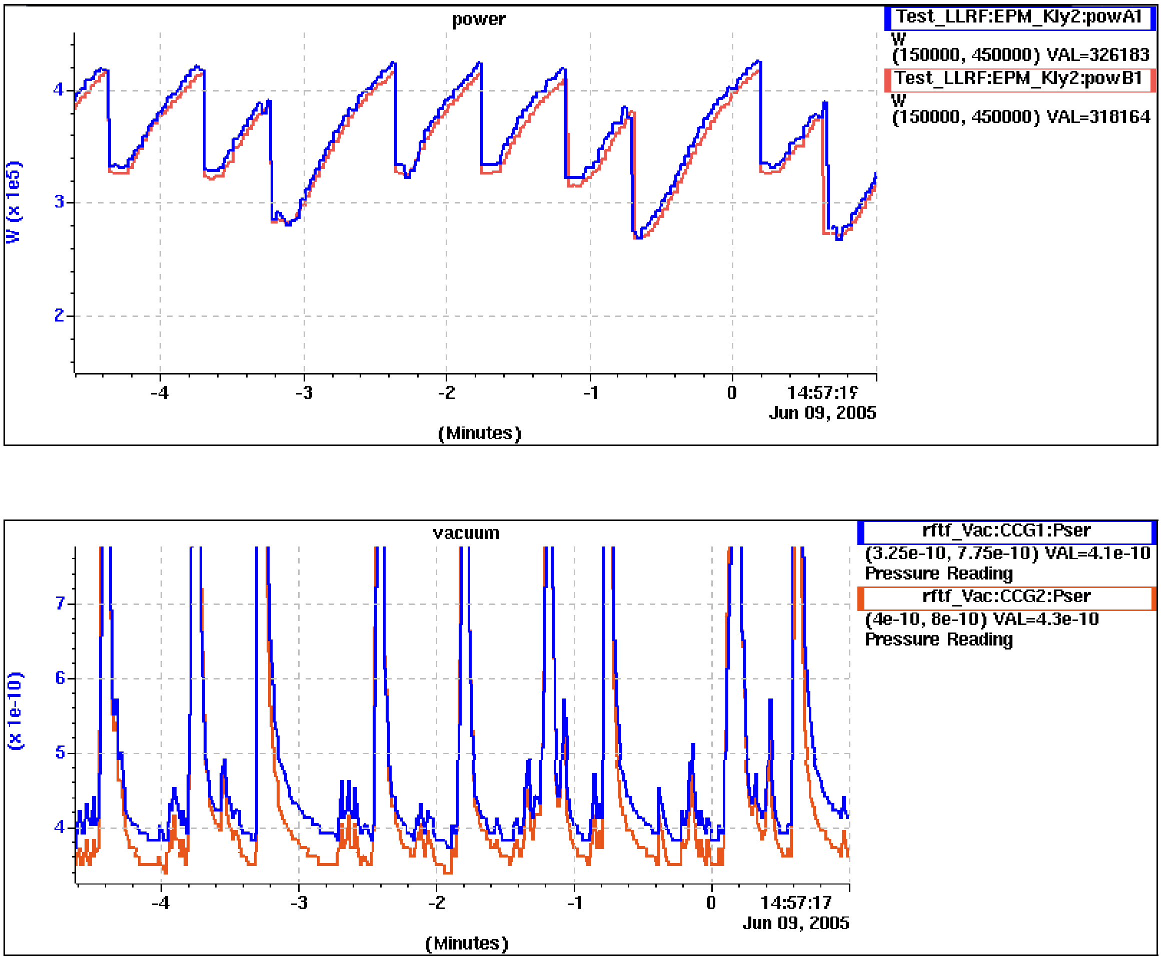


Figure 5.15: RF power backs off when vacuum crosses the predefined upper limit.

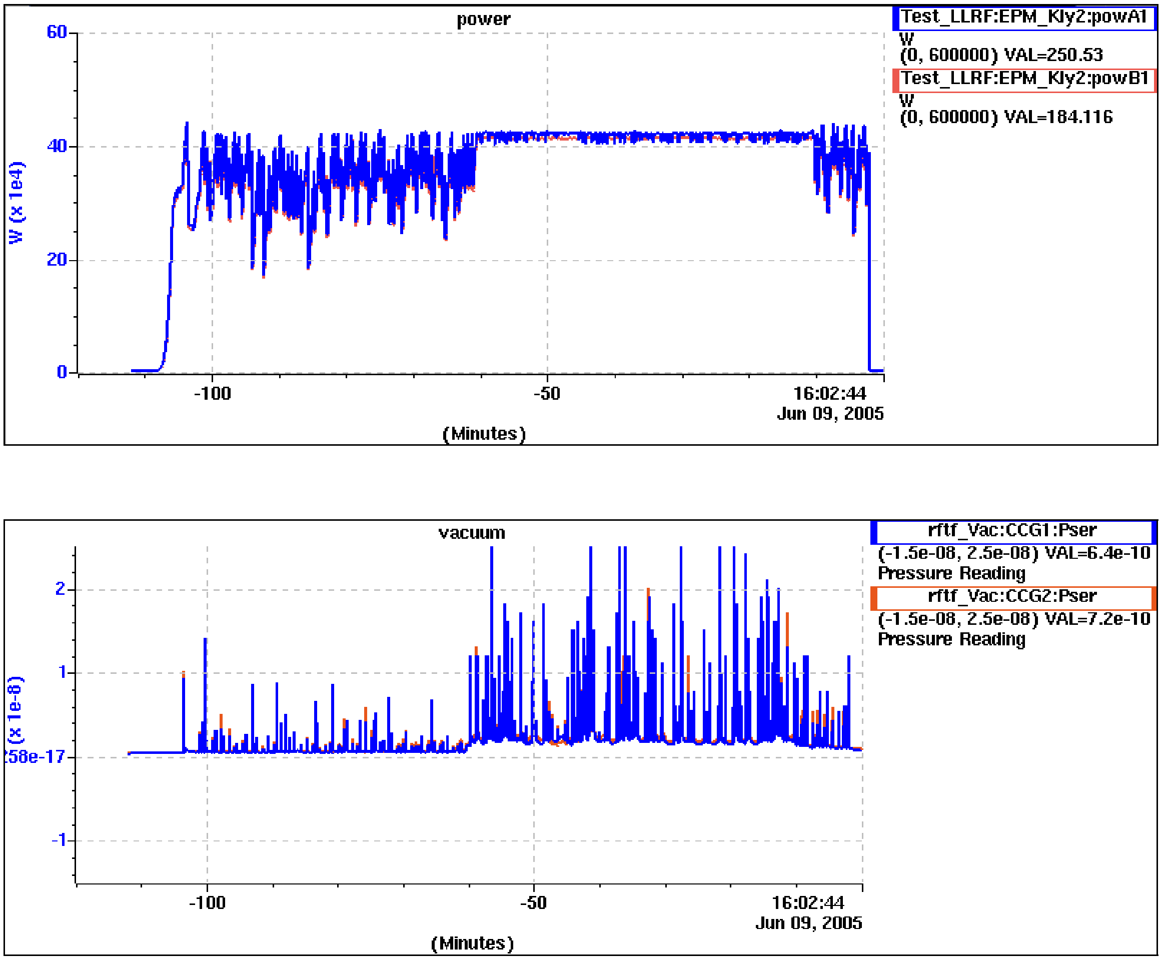


Figure 5.16: Two hour conditioning data in traveling wave mode.

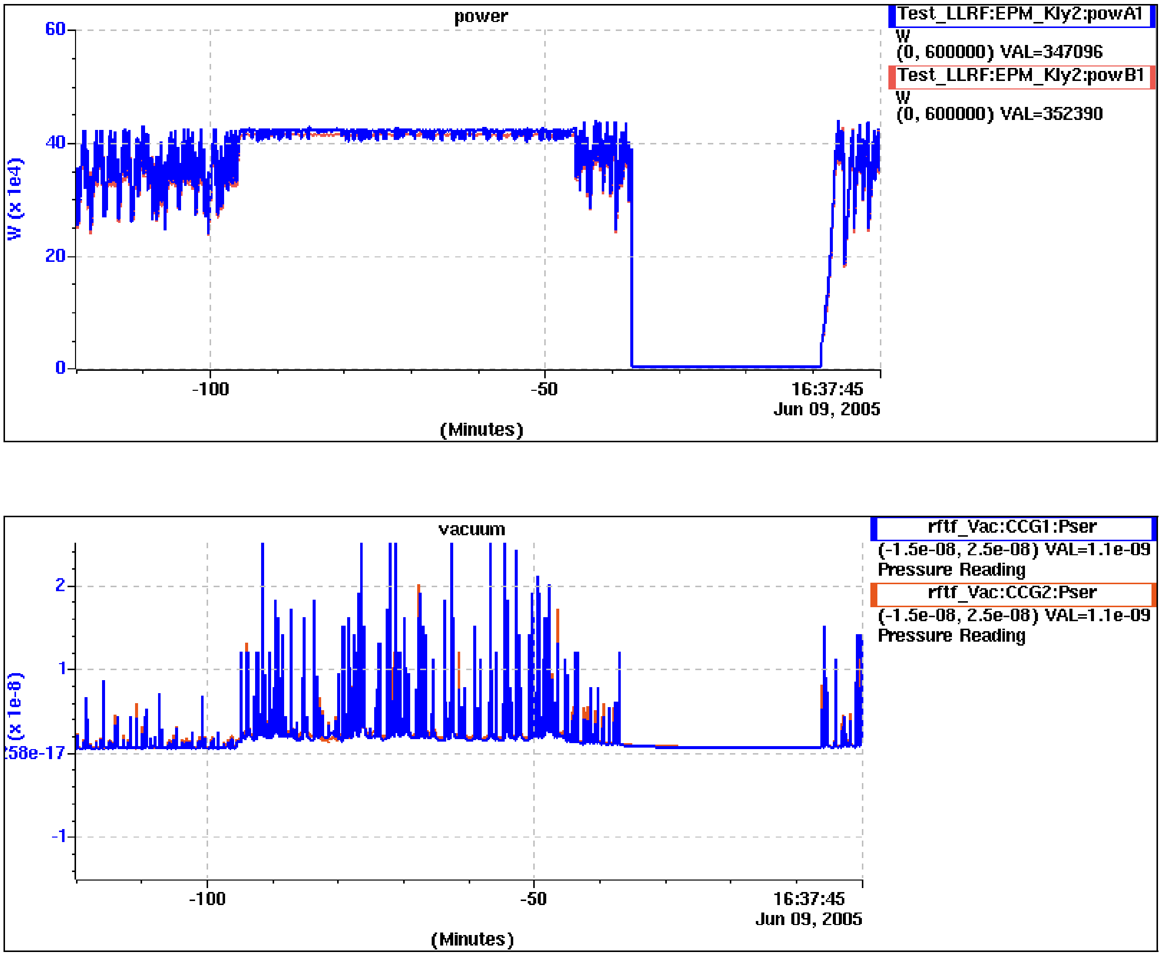


Figure 5.17: Power has been shut off during the modulator fault.

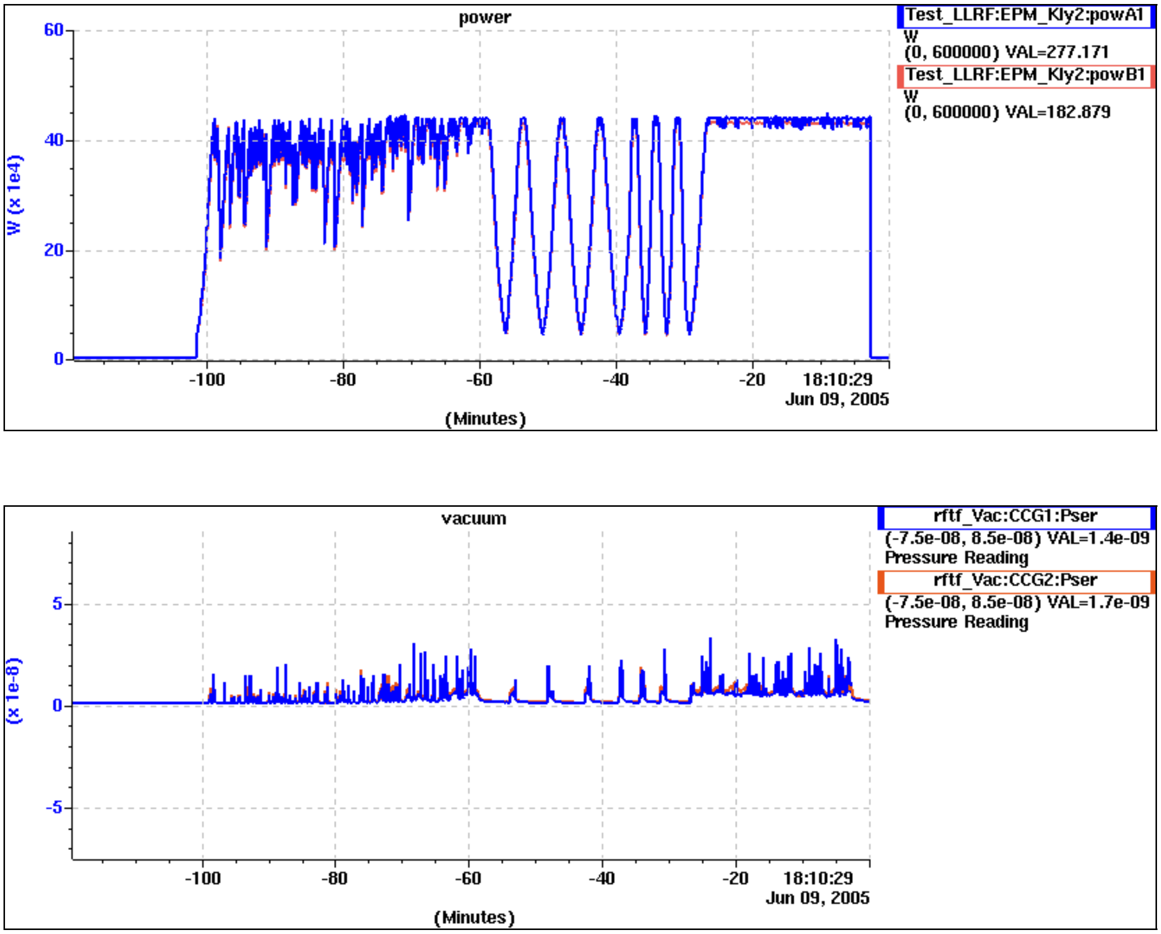


Figure 5.18: Auto cycle and constant power conditioning in traveling wave mode.

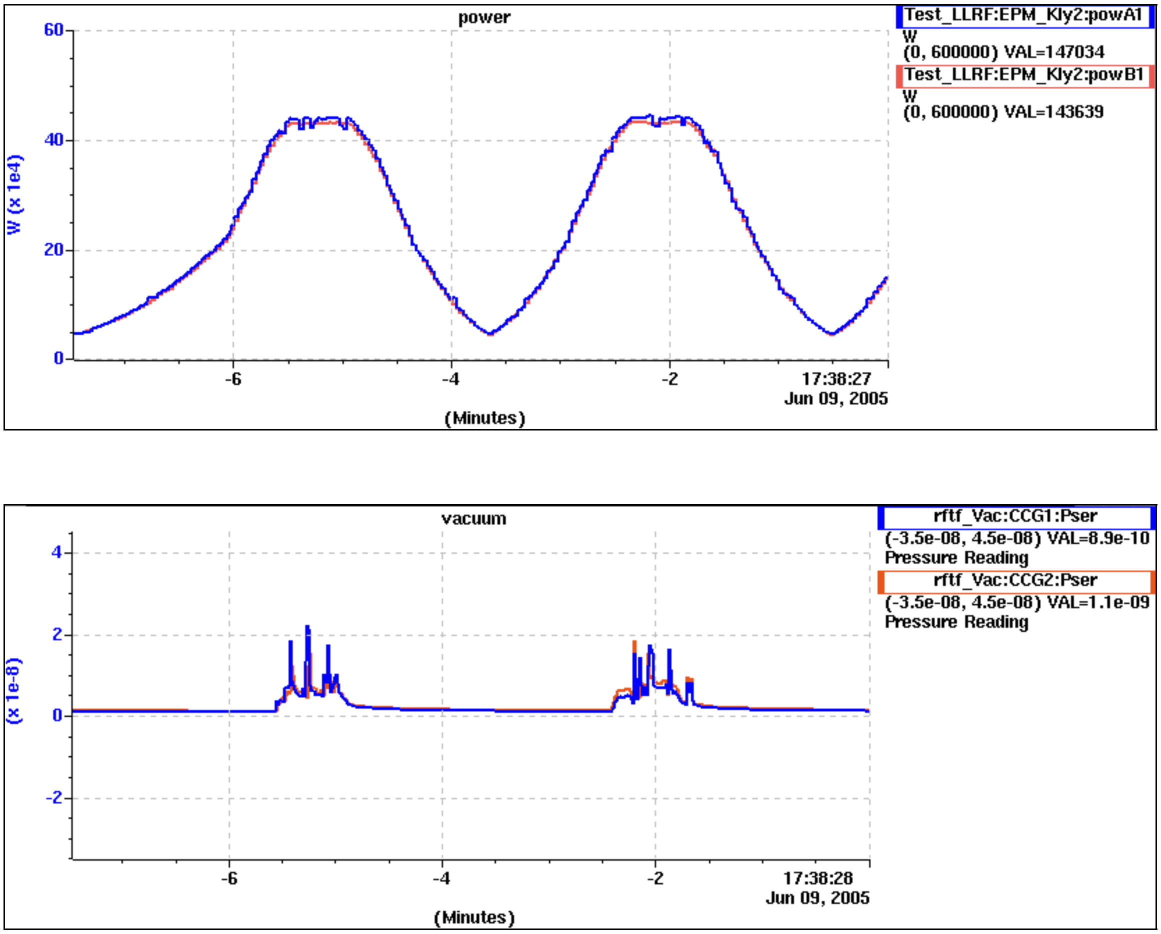


Figure 5.19: The effect in vacuum during the auto cycle conditioning.

5.4.3 Results in Standing Wave Mode

The matched load is replaced with a variable short to condition the couplers in standing wave mode. Several data has been presented here. In the power graph, blue and green color represents the input and output forward powers, respectively, and in the vacuum graph they represent the vacuum pressure of the first and second couplers, respectively. Figure 5.20 shows the one-hour conditioning data during the standing wave mode. In the Figure 5.21, auto cycle and constant power conditioning in the standing wave mode has been shown. The difference between the input and output forward power has been much noticeable than the transmission wave mode. Since the wave is being transferred back and forth through the couplers in the standing wave mode and the positions of the directional couplers are fixed, this measurement difference has been occurred. Arcing was happening for several times during the standing wave conditioning and RF power was shut down by the system at that time. Figure 5.21 shows these results.

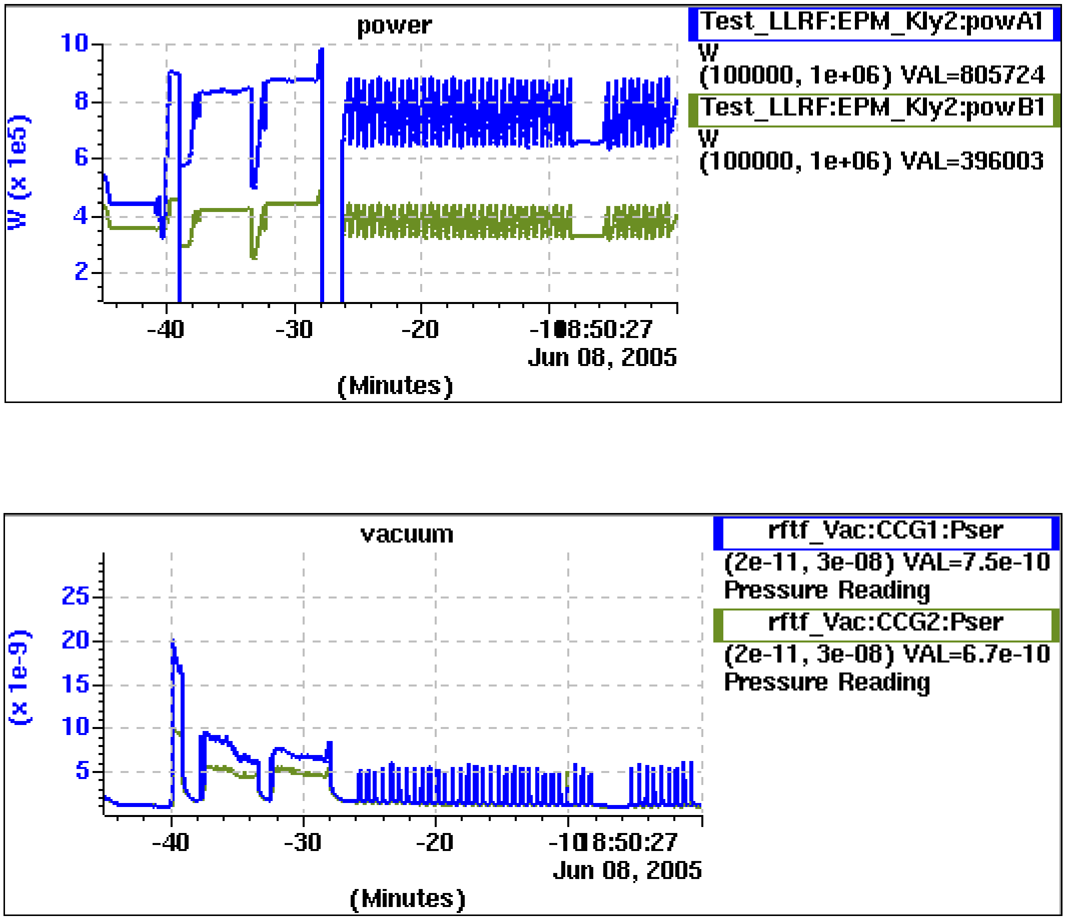


Figure 5.20: RF conditioning in standing wave mode.

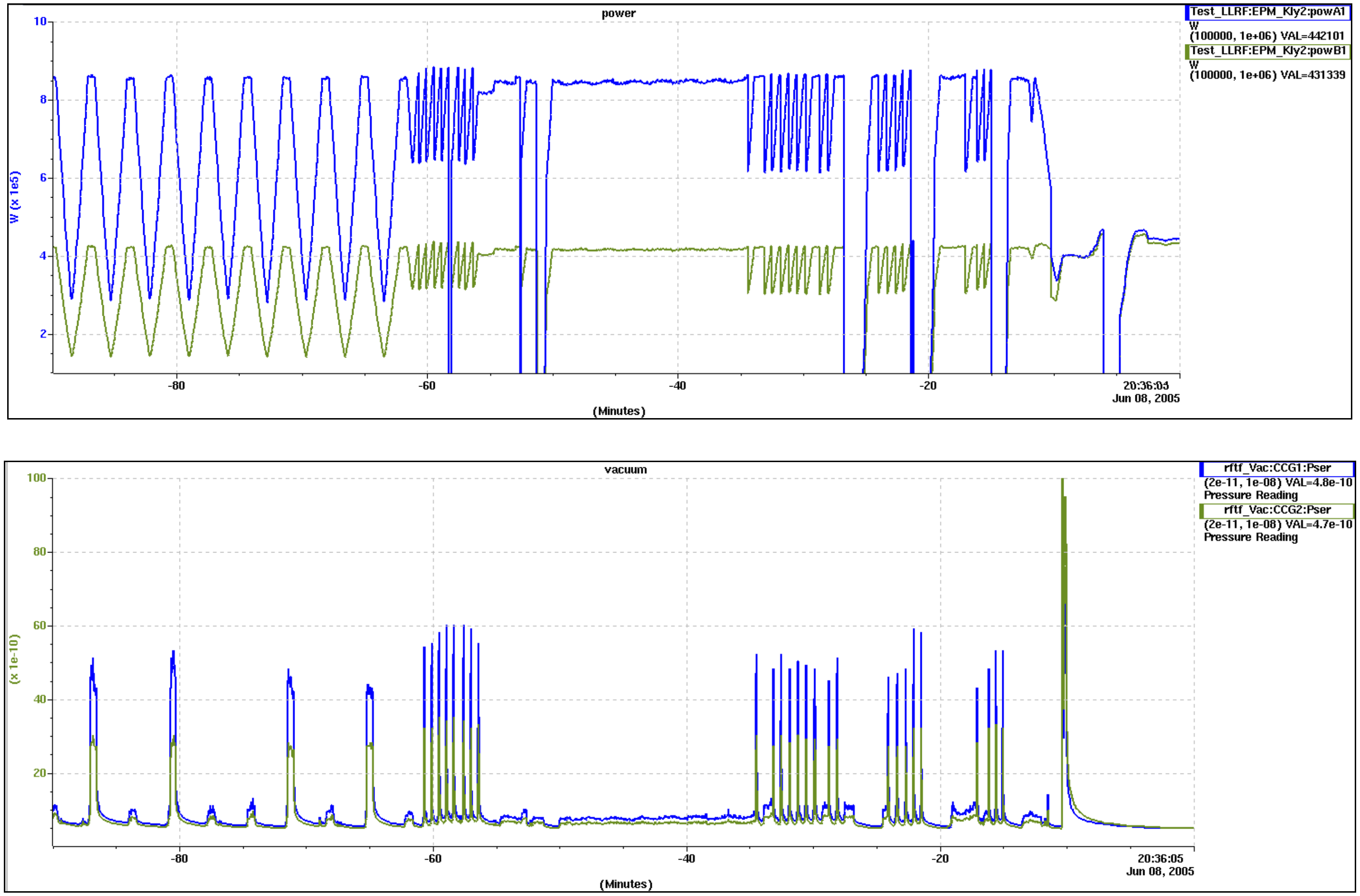


Figure 5.21: Auto cycle and constant power conditioning in standing wave mode

Chapter VI

Conclusions and Future Research

6.1 Conclusions

Extensive research should be performed in material sciences to build and search the next generation materials for the aircraft, computer memory cells, electronic devices, automobiles, high temperature superconductors, new fuel cells, new drugs and medicine. For fulfilling these purposes, many accelerator facilities are being built around the world to produce neutron sources, synchrotron X-ray sources, etc, to understand and analyze materials at the atomic level. Moreover, with the advancement of the accelerator technology the research in the high power RF field is advancing. Since, RF power is the only source to energize the beam in the high-energy accelerators, it is very important to supply this power efficiently. Usually a large number of RF windows and couplers are used in an accelerator facility and they should be conditioned before installed on the actual system to avoid any kind of catastrophic failure. So, it is necessary to have an automated reliable RF conditioning system for saving time and money.

The research described in this thesis has been performed by focusing on implementing such conditioning system integrated into EPICS environment that is the common control platform of large-scale scientific instrumentation. Although the proposed RF conditioning system has been designed for conditioning the RF windows used in the accelerators, this system can be applied to condition various RF materials and windows used in any field or applications; it can be called a universal RF conditioning system. The achievement of the research can be summarized as follows-

- **Simple design with state-of-the-art instruments:** The proposed RF conditioning system is simple yet robust. It has been designed by using some state-of-the-art instruments from the commercial companies, which are available in the market. Custom made instruments have been avoided throughout the design to make it more affordable to the other users. The use of PLC for the interlocking made this system more reliable. Proper communication protocols and hardware have been selected to communicate with the instruments. Moreover, the cabling and wiring between the instruments and IOCs have been designed, implemented and documented. All the IOCs and PLC have been programmed to perform the required tasks.

- **Automated control system with user friendly Operator Interfaces:** An EPICS based control system has been designed to automate and control the RF conditioning process. The designed control system is flexible, easy to manage and it can be controlled from anywhere throughout the network or internet. User friendly Operator Interfaces have been designed to control the process, to set the parameters, to monitor all the measurements, to plot the results and to archive the data.

- **The complete system has been tested in various wave modes:** The designed RF conditioning system has been tested by conditioning some couplers in various wave modes, such as travelling wave mode and the standing wave mode. The performance of this control system is highly satisfactory.

6.2 Future Research

Some suggestions for the future research in this field has been summarized below-

- More research work should be performed to interlock the water-cooling system.
- Synchronize with the klystron and modulator fault.
- More intelligence to select the soft limits automatically to further minimize any manual control.

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Vita

S.M. Shajedul Hasan was born in Narsingdi, Bangladesh on January 4, 1978. The prime minister of Bangladesh awarded him for his outstanding results in the Higher Secondary Certificate (H.S.C) and Secondary School Certificate (S.S.C) examination in the year of 1995 and 1993 respectively. Mr. Hasan received his Bachelor of Science degree in Electrical and Electronic Engineering from Bangladesh University of Engineering and Technology (BUET) in March 2002. He was awarded the dean scholarship throughout his undergraduate studies. Moreover, he got First prize in the 'IEEE Myron Zucker Student Design Award' for designing 'Microcontroller based Prepayment Energy Meter' when he was a senior student in his undergraduate. The prize was given at IEEE Industry Application Society (IAS)'s Annual Conference at Chicago, IL, USA in the year of 2001.

In August 2003, he joined the University of Tennessee, Knoxville (UTK), as a Masters student in the Department of Electrical and Computer Engineering (ECE). Before joining UTK, he worked in BUET as a research engineer. Currently, he is working with the RF group of Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), as a Graduate Research Assistant. He also worked as a Teaching Assistant in the Department of ECE of UTK for one year. Mr. Hasan's research interest is in RF and wireless communication area. He is also expert in the field of instrumentation and measurement.